Tank Sealing with Coating Materials

U.S. DEPARTMENT OF TRANSPORTATION
Maritime Administration
in cooperation with
Todd Pacific Shipyards Corporation

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 1983**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Tank Sealing With Coating Materials**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Surface Warfare Center CD Code 2230-Design Integration Tower Bldg 192, Room 128 9500 MacArthur Blvd Bethesda, MD 20817-5000**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**91**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

September 1983

THE NATIONAL SHIPBUILDING RESEARCH PROGRAM

Tank Sealing with Coating Materials

U.S. DEPARTMENT OF TRANSPORTATION
Maritime Administration
in cooperation with
Todd Pacific Shipyards Corporation

FOREWORD

This report compliments another, "Improved Tank Testing Methods - January 1980." which was also produced as part of the National Shipbuilding Research Program (NSRP). The commmon objective is to create assurances that would substitute for hydrostatic tests of tanks. Such tests adversely impact on shipbuilding productivity and schedules because of the work and time durations required for filling and draining large volumes, because of the. extraordinary loads imposed on building berths and because of environmental concerns for drainage.

Further, such tests are recognized by even ship classification societies as inadequate for assuring strength as they do not anticipate dynamic and sloshing loads. Thus, except for radically different structural designs and ships of extraordinary size, hydrostatic tests create dubious strength assurances. An American.Bureau of Shipping vice president introduced the idea that statistical control of manufacturing, such as described for hull construction in the NSRP publication "Process Analysis Via Accuracy Control - February 1982" could create better assurances for strength.

Regarding tightness, the earlier research disclosed that productivity could be improved by the use of ultronics for leak detection in lieu of a soap solution during pneumatic tests. Because ultrasonic detectors are less sensitive than a soap solution for minute flaws equivalent to 10 roils in diameter and smaller, the primary goal of the project described herein was to demonstrate that normally used tank coatings effectively seal such flaws over the expected lifetimes of the coating systems.

Representative tank coating systems were obtained and tested to evaluate their effectivenes in sealing weld flaws and holes of known diameter. Leak tests at pressures up to Opsig were--performed on coated specimens both before and-after accelerated aging tests. Specimens were aged at elevated temperatures in salt water, methanol/water and JP-4. The tests simulated up to twenty years of service life in salt water and the coatings were exposed to the coating manufacturers' recommended and non-recommended requirements. Test results revealed that the leak sealing effectiveness of "recommended" coatings was 99.6% and that the leak sealing effectiveness of "non-recommended" coatings was 9.8%. S-s were often maintained by the coatings even after complete surface debonding. Sections through flaws showed that the coatings penetrated into the holes and maintained the seal even after surface breakdown. The effects of mechanical stress on the coatings were addressed for elastic substrate behavior. Theoretical considerations show that the coatings will not he adversely affected.

In consideration of the research accomplished, the vice-president of the American Bureau of Shipping verbally expressed willingness to revise tank testing requirements on a trial basis in response to specific proposals from one or two shipyards.

ACKNOWLEDGEMENTS

This report was produced for the Los Angeles Division of Todd Pacific Shipyards Corporation by Southwest Research Institute of San Antonio, Texas. The authors are E.B. Bowles and P.A. Cox. L.D. Chirillo of L.D. Chirillo Associates served as the R&D Program Manager in behalf of Todd.

Special appreciation is expressed to J. Peart of Avondale Shipyards, Inc. for pertinent information on surface preparation and coatings. Appreciation is also expressed to R.L. Bass, 111, W.A. Mallow, R.J. Sicard and D. Endicott of Southwest Research Institute and to T. Lamoureux, L. Willets, D. Arnold and B. Coralles of Todd's Los Angeles Division, all of whom furnished . essential support.

Valuable contributions, coating samples and expert advice, were made by the following coating manufacturers:

Ameron Corrosion Control Division
Carboline Company
Hemphill Marine Paints, Inc.
International Paint Company
Sigma Coatings, Inc.
Wisconsin Protective Coatings, Inc.

This report is an end product of one of the many projects managed and cost shared by Todd for the National Shipbuilding research Program. The program is a cooperative effort by the Maritime Administration's Office of Advanced Ship Development and the U.S. shipbuilding industry. The objective, described by the Ship Production Committee of the Society of Naval Architects and Marine Engineers, is to improve productivity.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

A. Purpose and Goals

The purpose of the project was to improve productivity in ship tank tightness testing. To improve productivity, new tank tightness testing methods, which are easier, faster, and at least as reliable as the current hydrostatic method, must be implemented.

An earlier study conducted by SWRI [1]* entitled "Improved Tank Testing Methods", January 1980, compared the standard hydro test to a number of other tightness testing methods. The study also performed a preliminary evaluation on how well ship tank coatings plug small pinhole-type flaws in tank boundaries. Results of this work found that (1) greater assurance of tank tightness is provided by a low pressure air and soap test than by a hydrostatic test, (2) in a laboratory environment, tank coatings can effectively seal flaws which are much larger than the minimum flaw size detectable by current tightness testing methods, and (3) only ultrasonic detection methods show potential for improving productivity in ship tank testing.

The sensitivity of an ultrasonic test is less than that achieved with air and soap, so, for this method to be accepted as a replacement test, sensitivity requirements must either be reduced or the use of coatings to seal small flaws (less than 8 roils in diameter) must be accepted. Using ultrasonic detection, in lieu of a soap solution, only means that flaws in the range of 2 roils to 8 roils (equivalent hole diameter) are not detected and repaired before coating. These are very small flaws and should pose no problems with tank structural integrity, particularly since weld quality is established by a separate survey. Thus, the primary goal of the current project was to demonstrate that coatings permanently seal small flaws in ship tanks. Secondary goals were to have ABS accept the use of tank coatings for sealing flaws in ship tanks that are below the practical detectability limits of ultrasonic detectors and to have ABS accept the use of ultrasonic detection in lieu of a soap solution in tank tightness testing.

References listed at the end of the report.

B. Background Information,

AS background information for the current study, key results of the previous work, "Improved Tank Testing Methods", [1] are summarized in the following paragraphs.

In order to evaluate the accuracy of the various tightness tests, it was necessary to determine the minimum hole or flaw size that could be detected by each method. The information shown on Figure 1 indicates the relative sensitivity of a hydrostatic test and a low pressure air and soap test. In a low pressure air and soap test, air is used to pressurize the tank, thus, forcing air out through any holes in the tank boundary. The exterior of the tank boundary is coated with a soap film, and air leaking across the boundary forms soap bubbles. This provides a clear indication of where small pinhole-type leaks exist in the tank walls. Typically, a shipbuilder performs an air and soap test in order to detect and repair as many leaks as possible before hydrostatically testing for tank tightness.

From Figure 1, one can see that an air and soap test with a pressure differential of 2 psig can detect a hole as small as 2 mils in diameter. The hydrostatic test has a variation in minimum detectable hole size since the differential pressure is a function of the height of the water in the tank. However, for a tank that is 100 feet deep, the minimum detectable hole size (at or near the bottom of the tank) is slightly less than 2 roils in diameter. Near the tank top, the minimum detectable hole size is between 3 and 5 mils in diameter. Comparing the two methods, there is little difference in the accuracy of (1) a 2 psig air and soap test and (2) a hydro test. In addition, the air-test would be more likely to uncover leaks over the entire surface area of any size tank than would a hydro test since the detectable hole size of the hydro test is a function of the water level in the tank.

In addition to the tests for determining the minimum detectable hole size for the hydrostatic and air and soap tests, a comparison test was conducted on a number of fillet weld flaws to see which test, either

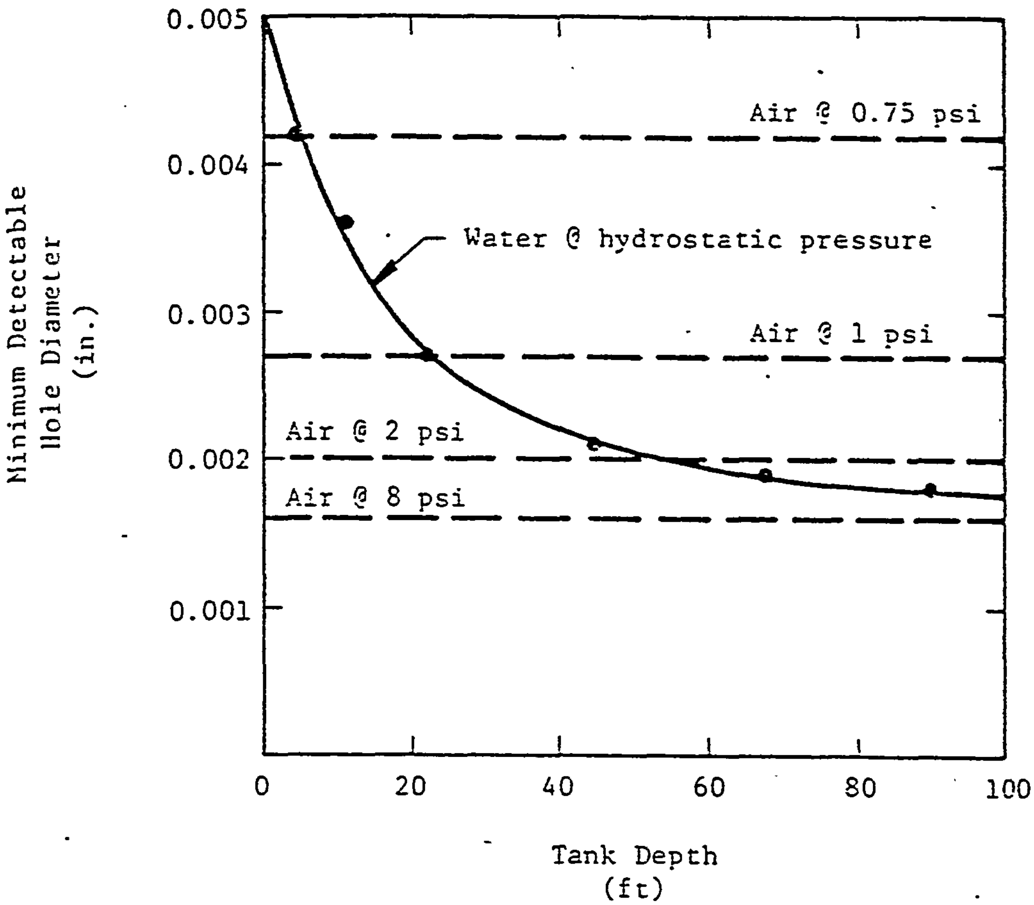


FIGURE 1. MINIMUM DETECTABLE HOLE DIAMETER VS TANK DEPTH

the hydrostatic or air and soap test, uncovered the most flaws. The results of the comparison are presented in Table I. The results show that for a differential pressure of 2 psig, the air and soap test uncovered a total of 122 flaws while the 50 psig hydro test detected 129 flaws. This means 95% of the flaws found with the hydro test were also found with an air and soap test with a pressure differential of 2 psig. In addition, for a maximum pressure level of 50 psig, the air and soap test detected 7% more flaws than did the hydro test. The comparison test demonstrated there is little difference in the accuracy of a hydrostatic test and an air and soap test for detecting small flaws in weldments.

Besides the tests conducted with water and air and soap, tests were also run to determine the accuracy of two ultrasonic detection techniques. The first test was to evaluate an ultrasonic technique where the tank is pressurized with air (again with a differential pressure of 2 psig across the tank boundarv) causing air to rush through any holes in the tank boundary. The air passing through the holes creates air turbulence which generates noise in the range of 36 to 44 kilohertz. This noise can be detected with an ultrasonic listening device. For this test, the "flaw" to be detected was a stainless steel tube three-eighths of an inch in length and of known inside diameter. The test results are included in Table 11. number of the holes were not detected because the air flow rate through the holes was not sufficient for generating the air turbulence. As one can see from the table, the minimum detectable hole size for a differential pressure of 2 psig is slightly larger than 7 roils. This means this ultrasonic method cannot detect holes as small. as can be detected by hydrostatic or air and soap testing.

The other ultrasonic technique that was. evaluated utilized an ultrasonic generator to produce detectable ultrasonic noise. With this method, an ultrasonic generator is placed in the tank. Ultrasonic noise then travels through any openings in the tank boundary. Flaws are detected by a listening device located outside of the tank. For this evaluation, the “flaws” were the stainless steel tubes used in the ultrasonic test described above. The results of the ultrasound generation evaluation are presented in Table III. As with the previous ultrasonic method, the minimum detectable hole size was determined to be approximately 7 roils.

TABLE I. LEAKS DETECTED IN WELDMENTS BY AIR (AND SOAP) AND WATER TESTS

Pressure Level* For Leak Detection (psig)	Number of Leaks Detected	
	Air and Tercetyl Soap Solution	Water
1.0	116	103
2.0	6	6
5.0	5	5
10.0	7	5
20.0	1	4
30.0	1	0
40.0	1	3
50.0	1	3
Total Number of Leaks Detected	138	129

*Maximum Pressure Level Of 50 psig

TABLE 11. DETECTION DISTANCE FOR ULTRASONIC PROBE AS A FUNCTION OF AP AND) HOLE SIZE

Minimum Pressure Drop Along Length of the Tube (psig)	Naximum Distance From Leak At Which DetecLion Is Possible (ft)					
	Hole Diameter (in.)					
	0.0042	0.0061	0.0073	0.0103	0.0142	0.0338
1.0	ND	ND	ND	ND	1	20
2.0	ND	ND	15	15	25	> 30
4.0	ND	ND	15	20	30	>30
6.0	ND	15	25.	30	> 30	> 30
8.0	ND	15	25	> 30	> 30	> 30
10.0	Nl)	25	30	> 30	> 30	> 30

ND = Not Detectable

TABLE III. DETECTION DISTANCE WTTH THE SOUND GENERATOR

Hole Diameter (in.)	Maximum Distance From Leak At Which Detection is Possible (ft)
0.0C61	ND
0.0073	4
0.0103	8
0.0142	10
0.0338	10

N) = Not Detectable

*Soncaster Noise Generator Used for All Tests

Since the ultrasonic test would be faster, easier, and less expensive to conduce than the hydro test or air and soap test, it was de-tided to investigate ways of making the accuracy of the ultrasonic test comparable to the hydro and air and soap tests. One possible way of achieving this goal would be to use a coating to permanently seal small holes that the ultrasonic method cannot detect. This means that if holes less than approximately 8 roils in diameter can be plugged by the tank coating, then the ultrasonic method would detect any and all larger, unplugged holes. Therefore, an investigation was undertaken to study how well ship tank coatings seal small flaws.

A series of holes of known diameters were drilled,into a set of one quarter inch thick steel plates. The plates were then coated with some of the more popular ship tank coatings on the market in late 1979. Before the plates were coated, the ultrasonic method could detect all of the holes (the smallest hole being 40 roils in diameter). Typical results from ultrasonic tests conducted after the plates were coated are presented in Tables IV and V. The results of these tests demonstrated that small holes can be plugged by coatings at pressures well above hydrostatic pressures that occur in integral ship tanks. If the coatings are not erroded away or weakened over a period of years then the seals may be permanent; however, there is also an uncertainty about the effect of ship hull stresses produced by the hydrostatic loads and the “working” of the ship at sea. The possibility exists that loads of this nature could cause a coating to break apart or detach from the wall surface or a flaw to enlarge or expand. Either of these problems could allow leaks to develop after a period ef time.

Based on these findings from the earlier project, it was decided chat the ultrasonic detection method showed potential for replacing the present hydrostatic test procedure for testing ship tagk tightness. However, in order for the regulatory agencies, shipowners, and shipbuilders to accept this new procedure, it would be necessary to prove that (1) tank coatings can be used to permanently seal pinhole-size (8 roils or less in diameter) flaws in ship tanks and that (2) the ultrasonic detection method is as accurate or more accurate and more cost effective than the

TABLE IV. LEAK DETECTION RESULTS ON TEST HOLES* BRUSH COATED WITH CARBOLINE INTERNATIONAL'S PHENOLINE 373 PRIMER AND COATING**

Hole Diameter (inches)	Pressure Level*** for Leak Detection (psig)
0.0400	ND
0.0420	ND
0.0465	ND
0.0550	ND
0.0635	ND
0.0700	ND
0.0760	ND
0.0810	ND
0.0860	ND
0.0935	ND
0.0980	ND
0.1015	ND
0.1065	ND
0.1110	ND
0.1285	ND
0.1405	ND
0.1470	ND
0.1520	ND
0.1570	ND
0.1610	ND

* Test holes drilled in l/4-inch steel plate .

** mating applied with a brush

*** Maximum pressure level of lSO psig

ND - Not detected

TABLE V. LEAK DETECTION RESULTS ON TEST HOLES SPRAY COATED WITH CARBOLINE INTERNATIONAL'S PHENOLINE 373 PRIMER AND COATING***

Hole Diameter (inches)	Pressure Level*** for Leak Detection (psig)
0.0400	ND
0.0420	ND
0.0465	ND
0.0550	ND
0.0635	ND
0.0700	ND
0.0760	HNP
0.0810	HNP
0.0860	HNP
0.0935	HNP
0.0980	HNP
0.1015	HNP
0.1065	HNP
0.1110	HNP
0.1285	HNP
0.1405	HNP
0.1470	HNP
0.1520	HNP
0.1570	HNP
0.1610	HNP

* Test holes drilled in 1/4-inch steel plate

** Coating applied with a spray gun

*** Maximum pressure level of 150 psig

ND - Not detected

HNP - Hole not plugged by test coating, i.e., a paint film did not form over the hole during spraying.

hydrostatic test. The current project was designed to prove that tank coatings permanently seal pinhole.type flaws in tank boundaries.

C. Approach

As stated previously, the primary goal of this project was to demonstrate the effectiveness and durability of tank coatings as seals for small flaws in integral ship tanks. To achieve this goal, a series of laboratory tests were planned and conducted to evaluate the leak sealing capabilities of typical coating systems. The approach followed is outlined below:

o Search.for related work
  - conduct suney of open literature
  - make inquiries through coating manufacturers
  - contact shipbuilders

o Obtain coatings for testing
  - identify major manufacturers of marine coating systems
  - select representative samples of tank coating systems
  - requisition and purchase tank coatings

o Develop tests to simulate in-service conditions
  - identify aggressive tank cargos
  - develop accelerated aging tests

o Determine effectiveness of coatings to initially seal flaws
  - design test specimens
  - create and identify flaws
  - prepare and coat specimens
  - conduct air and soap tests
  - identify unsealed flaws

o Determine durability of coating seals
  - conduct accelerated aging tests in three environments
  - visually evaluate coatings -
  - test specimens for leaks
  - section specimens to examine seals

In addition to the primary goal of this project, two secondary goals were ABS acceptance of (1) the use of coatings to seal small flaws in ship tanks and (2) the use of ultrasonic detectors, in lieu of a soap solution, in tank tightness testing. Steps taken to accomplish these goals were:

- Seek ABS participation
  - brief ABS on the project
  - request criteria of acceptance for the use of coatings to seal small flaws in ship tanks
- Evaluate ultrasonic leak detectors
  - perform laboratory tests on representative model
  - evaluate sensitivity relative to a soap solution
  - evaluate use of ultrasound generator
  - test for interference by welding, grinding, and chipping

Documentation of the work performed to reach.the goals of this project, and the results obtained, are given in the following sections.

II. ESTABLISH IN-SERVICE CONDITIONS AND COATING PROPERTIES

A. Literature Search

A literature search was conducted early in the project to uncover research that may have already been performed on the sealing ability and durability of tank coatings. Specifically, we sought the following information:

- Names of coating manufacturers.
- Results on durability tests of coatings.
- Results on leak sealing capabilities of coatings.
- Information on surface preparation and coating application.
- Information related to accelerated aging of coatings.
- The effects of different types of cargos on typical coatings for marine application.

This literature search was conducted in the SWRI Technical Library, and included the Maritime Research Information Semite (MRIS), the Engineering Index, miscellaneous books and publications, and pertinent computerized data bases. Data bases included in the computerized literature search were:

- NTIS - National Technical Information Sefice.
- COMPENDIX - Computerized Engineering Index.
- Service Coatings Abstracts.
- ISMEC - The Mechanical Engineering Information Service.
- Oceanic Abstracts - National Oceanic and Atmospheric Administration.
- CA Search - American Chemical Society.

For the computerized searches, a number of different descriptors were used which included the following key words:

o tank	o container	o coat	o paint
o primer	o sealant	o ship	o marine
o evaluate	o durability	o aging	o tightness
o test	o leak	o detect	o performance
		o weather	o sealability

Using these key words descriptors were developed for five different literature searches. These descriptors are given in Table VI.

TABLE VI. DESCRIPTORS FOR THE COMPUTER LITERATURE SEARCH

Search I:	[Tank- Container-] and [Coat- Paint- Primer- Sealant-] and [Ship- Marine] and {[Performance Weather- Evaluate- Durability Aging] or [Tightness Sealability Test-]}
Search II:	[Tank- Container-] and [Coat- Paint- Primer- Sealant-] and {[Performance Weather- Evaluate- Durability Aging] or [Tightness Sealability Test-]}
Search III:	[Tank- Container-] and [Coat- Paint- Primer- Sealant-] and [Leak- Detect-]
Search IV:	[Tank- Container-] and [Coat- Paint- Primer- Sealant-] and [Leak-] and [Detect-]
Search V:	([Tank- Container-] and [Coat- Paint- Primer- Sealant-] and [Ship- Marine] and {[Performance Weather- Evaluate- Durability Aging] or [Tightness Sealability Test-]}) or ([Tank- Container-] and [Coat- Paint- Primer- Sealant-] and [Leak-] and [Detect-])

From the manual and computerized searches, a total of eighty publications were identified which appeared to have some relevance to this project. These publications are listed as references. An abstract of each publication was reviewed and thirty-seven papers were selected for further study. A study of these papers uncovered no research other than that conducted at SWRI [1] which addressed the leak sealing capabilities of coatings. It did, however, provide information on coating manufacturers, on cargos that are particularly detrimental to coatings, on aging tests for coatings to determine their long term durability, and on methods of coating application.

Reference 78 listed thirteen paint manufacturers who produce coatings for service in ship tanks. The paper discusses the types of primers and coatings currently being used for this application. The paper also presents test data evaluating the corrosion resistance of a number of popular coatings. Coating performance data is given for specimens which underwent 2,500 hours of salt spray testing.

Reference 6 presents a discussion of several types of aging processes. This reference mentions a fresh water immersion test, a salt spray test (ASTM,spec. B 117-49T), an under rust test, and a Cleveland condensing humidity test (ASTM spec. D-2247, Appendix II) as potential methods for evaluating aging effects on paint coatings. The paper also indicates that mechanical action, humidity, and chemical influences strongly affect coating aging and deterioration.

References 76 and 80 both mention techniques for applying coatings in ship tanks. Both recommend stripe coating of all critical service areas, sharp exposed edges, bolts, rivets, welds, rat holes, lightening holes, and other similar areas. Striping should be performed with a brush between the application of the prime coat and the top coats. This procedure helps insure a good coating on areas most susceptible to aging and corrosion damage.

B. <u>Contacts with Paint Manufacturers</u>

From the literature survey and from contacts established during the work of Reference 1, twenty paint companies were identified which appeared to have experience in the development and manufacture of marine coatings. Of these twenty companies, listed in Table VII, nine were contacted and, of these, seven were selected as sources of technical information. In Table VII one or two asterisks identifies those paint manufacturers which were contacted and two asterisks identifies-those, manufacturers from which technical information was requested.

In all of our contacts with paint manufacturers, we explained the purpose of our investigations and gave a brief description of the test plan. Then from each company we requested their coating systems which were most applicable to marine applications, specifically interior type tank coatings, and technical data on those coating systems. The technical data requested included:

o Adhesion	o Surface Preparation
o Film Strength	o Edge Effects
o Flexibility	o Cure Time & Cure Condition
o Toughness	o Permeability
o Solids Content	o Environmental Resistance

Typically the information provided included the solids content, surface preparation, curing conditions, and the environmental resistance. In addition, we requested test results or refe~ences to tests pertinent to our investigation. From these inquiries we discovered one study which demonstrated the <u>bridging</u>* capability of a coating, but this coating was not particularly applicable to marine application. Though requested, paint manufacturers did not furnish information on accelerated aging testing of their coatings.

From our review of the technical information from the paint manufacturers, nine basic coating formulations were identified. These coatings are listed by the generic name in Table VIII and, within each generic group, by trade name. Note that all of the coatings are epoxies with different curing agents and components. For each generic group, one or more coating systems were identified and for each of these coating systems the actual formulation may be quite different.

*The coating's ability to cover and seal small holes, cracks or surface depressions.

TABLE VII . COATING MANUFACTURERS IDENTIFIED

Ameron Corrosion Control Division**
Anchor Coatings
Camrex Limited (England)
Carboline Co.**
DeVoe & Reynolds Marine Paint Co.**
Eureka Chemical Co.
Farboil Co.
Hemphill Marine Paints, Inc.**
Hexel Co@oration*
Imperial Coatings Corporation
International Paint Co.**
Mobile Chemical Co.
Mobil Paint Manufacturing Co.
M & T Chemicals
NAPKO Corp.
Porter Coatings, Inc.
Sigma Coatings Inc.**
Steelcote Manufacturing Co.
Thermal Chemical Co.*
Wisconsin Protective Coatings**

** Requested and received technical information on tank coatings.

* Contacted but no data requested.

TABLE VIII. IDENTIFICATION OF COATING BY GENERIC NAME

Generic Name	Trade Name **
Polyamide Epoxy	*Carboline 191 (Carboline) DEVRAN 215 (Devoe and Reynolds) *Amercoat 81/82 (Ameron)
Epoxy/Urethane	DEVKEM 251 (Devoe and Reynolds)
"New Technology" Epoxy	Bar-Rust 235 (Devoe and Reynolds)
Phenolic Epoxy -	*phenoline 373 (Carboline)
Ketimine Epoxy	DEVRAN 244Hs (Devoe and Reynolds) *Intergard TAA Series/TAA 423HS (International)
Amine Cured Epoxy	*Carboline 187 (Carboline) DEVRAN 234QC (Devoe and Reynol{s) *Hempel 1540 (Hempel) *Hempel 3544 (Hempel) *Amercoat 395 (heron)
Vinyl Ester	*plasite 4005 (Wisconsin)
Epoxy - Coal Tar	*Carbomastic 14 (Carboline)
Isocyanate Cured Epoxy	*Colturiet A9-HB (s.~gma)

* Coatings received.
**The following trade names are registered:

DEVRAN
Amercoat
DEVKEM
Bar-Rust
Phenoline
Plastite
Carbomastic

At the time of the survey, the coatings identified were representative of the state-of-the-art for marine application. A sample of each coating was requested from the suppliers, “and those coatings in Table VIII, which are identified by an asterisk, were received for testing. As will be discussed in later sections, only nine of these coatings were actually tested, which covered five of the nine generic groups. The vinyl ester (Plastite 4005) was not evaluated because it was not recommended by the manufacturer for any of the chemicals chosen for the environmental testing. The isocyanate cured epoxy, Colturiet A9-HB, provided by Sigma, was found to have the incorrect formulation and could not be applied. Small samples of this coating were requested, and the ratio of curing agent to epoxy appeared in error. The coating was too thick and set too fast to be applied.* No new.formulations of this paint were requested.

C. In-Service Conditions

From the literature survey and our discussions with coating manufacturers, we discovered that the range of potential in-service conditions and the number of tank coating systems is quite large. As noted in the preceding section, nine generic types-of coatings were identified, and several coating systems are available for each generic type. Further, in this survey several factors were identified as being important to the . sealing characteristics and service life of the coatings. These are:

- Type of cargo
- Coating application of technique
- Coating exposure
- Service temperature
- Mechanical stress applied to the coating

1. Type of Cargo

The number of different types of cargoswhich are transported by ship is very large; however, past experience has shown that salt water (ballast water) is one of the more severe cargos that a coating must withstand. Also, paint manufacturers have found that light fuel oil and

* Coating was mixed in the presence of a Sigma technical representative

methanol, alternated with water, can be very damaging to tank coatings. As a rough rule of thumb, coatings that stand up well to ballast water do not perform well when exposed to light fuel oil or alcohol. Thus, salt water, light fuel oil (JP-4), and methanol/water were chosen as appropriate cargos for the simulated in-service aging tests of the coatings. When . exposing the coating to methanol/water, the test was started with methanol exposure and the cargos were alternated without permitting sufficient time for the specimens to dry out."

2. Coating Application Technique

Almost all ship tank coatings are applied by airless spray although both airless and conventional spray techniques are permitted. In addition, it has been found that most manufacturers require striping . of all welds and sharp corners. Stripe coats are usually applied by brush and the coating is worked into any irregularities that might exist in weldments. To evaluate the effects of the coating application on the sealing of small flaws, some specimens were prepared with stripe coats on the welds and drilled holes and some were prepared without the stripe coats. All applications were made by conventional (compressed air) spray techniques, and the coating thickness was measured wet and dry for uniformity. Coated specimens were examined by three-different paint manufacturers to confirm that the coatings were properly applied. Preparation of the specimens is further discussed in Section IV.

3. Coating Exposure

Within the tanks, coatings can be totally submerged in the splash zone or in the vapor phase. This type of exposure affects the durability of the coating. The accelerated aging tests were conducted with one-half of each specimen submerged and with one-half of each specimen in the vapor phase. There was no splash zone but complete submergence and vapor usually represent the extrenks.

4. Service Temperature

. Coating performance is significantly affected by the service temperature which is generally accepted to be from about 32°F to 140°F.

To accelerate the environmental effects upon the coating, we chose to test the coatings at elevated temperatures. However, when choosing the appropriate temperature, it was important to set the temperature below the decomposition temperature of the coatings and ideally, below the maximum service temperature specified for the coating by the manufacturer. To establish the accelerating effects of the higher test temperatures, a nominal in-service temperature of 75°F was assumed.

4. Mechanical Stress

In considering the effect of mechanical stress on the coatings, we inquired of paint manufacturers to determine. what problems they have encountered. The concensus was that mechanical stress is not a problem for elastic substrate behavior. However, for conditions of high plastic straining, such as that associated with the bulging of plate structure, a cracking of the coating and/or coating debonding can occur. Because ships are designed to avoid gross plastic behavior, we have limited our consideration to elastic substrate behavior. A comparison was made between the physical characteristics of a typical coating (i.e., epoxy) and a steel substrate. To do this we compared the coefficients of thermal expansion, the elastic modulus, and the ultimate stress values for these two materials. The ratios are:

$$\text{Thermal Expansion:} \quad \frac{\gamma_{stl}}{\gamma_{epoxy}} \approx 1/3$$

$$\text{Elastic Modulus:} \quad \frac{E_{stl}}{E_{epoxy}} \approx 70$$

$$\text{Ultimate Strength:} \quad \frac{\sigma_{stl}}{\sigma_{epoxy}} \approx 10$$

What these properties show is that for a given elastic deformation of the substrate, the stress in the epoxy will be lower, relative to its ultimate value, than that produced in the steel. This implies that failure of the steel should occur before failure of the coating. The higher coefficient of expansion of the epoxy could lead to debonding, but this effect will

be evaluated in the tests in which high temperatures, higher than normal operating temperatures, will be applied to the specimens.

A summary of the in-service conditions, which will be used to develop the simulated aging tests, are given in Table IX.

D. Preliminary Laboratory Experiments

As a part of the previous project on tank testing methods [1], a group of twenty-four welded specimens were fabricated and leak tested. These specimens were assembled by joining one-quarter inch plates together with fillet welds as shown on Figures 2 and 3. The geometry of this weldment is similar to that found in wraps and collars at the penetration of longitudinal through transverse bulkheads in ship tanks. Originally, these specimens were used to evaluate the ability of tank coatings to seal weld flaws.

In the current project, the twenty-four welded specimens were retested with a humid aging test. A test procedure was developed that accelerates the aging of paint coatings. In this test, half of each coated weld specimen was submerged in salt water and half was exposed to the salt water vapor above the liquid surface. The test temperature was 180°F, and the relative humidity of the vapor phase above the liquid surface was 100%. One week of accelerated humid aging in this environment is equivalent to two years of in-service aging. For the humid aging test we conducted, the specimens were tested for a period of 192 hours (eight days). The purpose of this test was to evaluate how coating performance is affected by the aging process. The data from this test was used as background information for the development of the test procedures given in Section IV.C.

A visual inspection of each test specimen was made before and after the aging test. The general condition of each coating was noted. We were looking for physical changes, such as loss of adhesion, in the coatings caused by the aging process. The findings of the inspection

TABLE IX. SUMMARY OF IN-SERVICE CONDITIONS

Cargos	o Salt Water o JP-4 o Methanol/Water
Application	o Conventional Spray - Specimens with stripe coats on welds and drilled holes. - Specimens without stripe coats.
Exposure	o One-half of each specimen submerged o One-half of each specimen in vapor phase.
Temperature	o Service range estimated as 32°F to 140°F. o 75°F chosen as nominal operating temperature. .0 Temperatures elevated for testing. o Maximum test temperature maintained below decomposition temperature of the coatings.
Mechanical Stress	o Not important for elastic substrate behavior. o Differential thermal expansion simulated in the tests.

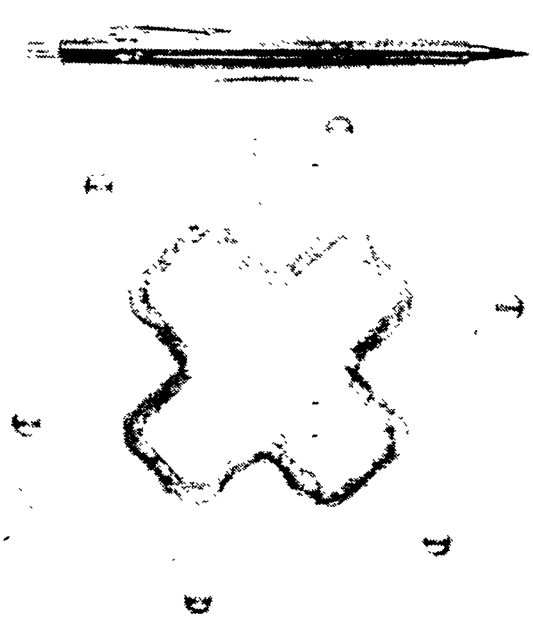


FIGURE 2. TYPICAL WELD SPECIMEN (PLAN VIEW)

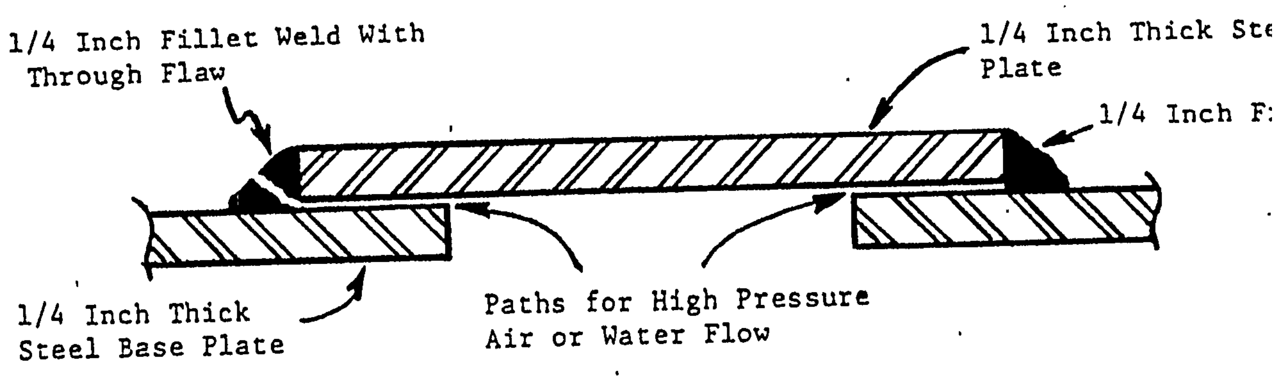


FIGURE 3. TYPICAL WELD SPECIMEN (CROSS-SECTIONAL VIEW)

procedure are summarized in Table X. .In the table, the term "water phase" refers to the segment of the test specimen submerged in the salt water and the "vapor phase" refers to the segment of the specimen exposed to the salt water vapor.

It is obvious from Table X that the "aging" process has significantly degraded the performance of some of the coatings while it has had little or no affect on others. After the coatings were "aged", a leak test was performed on the specimens. A standard air and soap test was used with Snoop as the detection soap. The test pressure ranged from 1 psig up to 50 psig. Test results are summarized in Table XI as are the results of the same leak test performed during the previous project before the coatings were "aged".

A comparison of the pre- and post- "aging" leak test results is quite revealing. The "aging' process has apparently sealed a number of leak holes in the weldments while it has exposed a number of others. It is possible that some of the holes, apparently sealed by the "aging", actually rusted shut during the time between the two leak tests. This period, which was more than one year in duration, also may have contributed to the aging process. During the period between tests, the weld specimens were stored in a laboratory work area in a cabinet at room temperature. In conclusion, the important result of this test comparison is that aging has adversely affected the leak sealing performance of a number of typical ship tank coatings.

TABLE X. EFFECT OF HUMID AGING TEST ON COATED WELD SPECIMENS

PAINT COATING	SPECIMEN NUMBER	ADHESION OF COATING AFTER AGING TEST	CONDITION OF COATING AT THE COMPLETION OF THE HUMID AGING TEST
Carbo Zinc 11 with Carboline 191 HB (CI)	1	Excellent	The water phase is more powdery than the vapor phase.
Not Painted	2	. .-	. --
HS Primer with Coating 24471 (DR)	3	Excellent	The humid aging test does not seem to have affected the coating.
Hempel 1540 (W) .	4	Excellent	A scratch test indicates the water phase is less durable than the vapor phase.
Zinc Primer 30207 with Coating 21556 (DR)	5	Fair	There is severe blistering on the water phase.
Carboline 191 HB (CI)	6	Excellent	The water phase is more powdery and less durable than the vapor phase.
Carboline 191 HB (CI)	7	Excellent	The humid aging test does not seem to have affected the coating.
Hempel 1540 (HMP)	8	Excellent	A scratch test indicates the water phase is less durable than the vapor phase.
Hempel 1540 (HMP)	9	Excellent	A scratch test indicates the water phase is less durable than the vapor phase.
Carbo Zinc 11 with Carboline 191 HB (CI)	10	Excellent	The water phase is more powdery than the vapor phase.
Carbo Zinc 11 with Carbomastic 15 (CI) -	1 1	Good/Fair	The water phase is thicker and softer than the vapor phase.
Carbo Zinc 11 with Carbomastic 15 (CI)	12	Good/Fair	The water phase is thicker and softer than the vapor phase.

TABLE X. EFFECT OF HUMIII ACTNC TEST ON COATED WELD SPECIMENS (cont.)

PAINT COATING	SPECIMEN NUMBER	ADHESION OF COATING AFTER AGING TEST	CONDITION OF COATING AT THE COMPLETION OF THE HUMID AGING TEST
Carboline 187 HFP (CI)	13	Excellent	The humid aging test does not seem to have affected the coating.
Phenoline 373 (CI)	14 .	Excellent	The humid aging test does not seem to have affected the coating.
Carboline 187 HFP (CI)	15	Excellent	A scratch test indicates the water phase is less durable than the vapor phase.
Phenoline 373 (CI)	16	Excellent	The humid aging test does not seem to have affected the coating.
Primer 20247 with Coating 21556 (DR)	17	Excellent	The humid aging test does not seem to have affected the coating.
Primer 20247 with Coating 21556 (DR)	18	Excellent	A scratch test indicates the-water phase is less durable than the vapor phase.
Primer 20247 with Anti-Corrosive ~3004 (DR)	19	Excellent	A scratch test indicates this coating has.worse scratch resistance than the other coatings.
Primer 20247 with Anti-Corrosi-ve 23004 (DR)	20	Excellent	A scratch test indicates this coating has worse scratch resistance than the other coatings.
Zinc Primer 30207 with Coating 21556 (DR)	21	Fair	There is severe blistering on the water phase.
Zinc Primer 30207 with Anti-Corrosive 23004 (DR)	22	Fair	There is severe blistering with water under the blisters on the water phase. There is some blistering and disintegration of the coating on the vapor phase.
Zinc Primer 30207 with Anti-Corrosiv 23004 (DR) 1	23	Fair/Poor	There is moderate blistering with water under the blisters on the . water phase. There is some disintegration of the coating on the vapor phase.

TABLE X . **EFFECT OF HUMID AGING TEST ON COATED WELD SPECIMENS (concluded)**

PAINT COATING	SPECIMEN NUMBER	ADHESION OF COATING AFTER AGING TEST	CONDITION OF COATING AT THE COMPLETION OF THE HUMID AGING TEST
HS Primer with Coating 24471 (DR)	24	Excellent	A scratch test indicates the water phase is less durable than the vapor phase.

( ) - Indicates name of paint manufacturer where:

DR is Devoe and Raynolds

CI is Carboline International

and HMP is Hempel's Marine Paints

TABLE XI. PRE AND POST HUMID AGING LEAK TEST COMPARISON FOR COATED WELD SPECIMENS

Test Technique: Air with soap solution

PAINT COATING	SPECIMEN NUMBER	HOLE NUMBER	PRE-AGING DETECTION PRESSURE LEVEL *(psi)	POST AGING DETECTION PRESSURE LEVEL *(psi)
HS Tank Primer and Coating 24471 (Devoe and Raynolds)	3	3 4	20.0 ND	10.0 10.0
Hempel 1540 (Hempel's Marine Paints)	4	1 2 3	ND ND ND	10.0 50.0 1.0
Carbo Zinc 11 with Carbomastic 15 (Carboline International)	11	3	ND	5.0
Phenoline 373 (Carboline International)	16	3 4	20.0 20.0	ND ND
Tank Primer 20247 with Tank Coating 21556 (Devoe and Raynolds)	17	2 3 4	30.0 40.0 40.0	20.0 10.0 ND
Tank Primer 20247 with Tank Coating 21556 (Devoe and Raynolds)	18	1 4 7	40.0 40.0 1.0	1.0 ND 1.0
Tank Primer 20247 with Anti-Corrosive 23004 (Devoe and Raynolds)	20	1 2 6 9	ND ND ND 1.0	10.0 50.0 10.0 1.0
Zinc Primer 30207 with Anti-Corrosive 23004 (Devoe and Raynolds)	22	4 5	5.0 5.0	ND ND

*Maximum pressure level 50 psi

ND - Not Detected

( ) - Indicates name of paint supplier

111. SEALANT CRITERIA

A. Establish Sealing Criteria for the Coatings

The ability of coatings to seal flaws in ship tanks is affected by the size of the flaw, the over-pressure level, and the length of time the coating has been in semice. Thus, to determine the ability of typical tank coatings to seal flaws or weeps in ship tanks, criteria were established in these three areas. That is, we established the maximum hole size that the coating must seal, the over-pressure level at which the seal must be maintained, and the number of years for which the seal must remin effective.

1. Flaw Size

In choosing the flaw size to be sealed, we recognized that coatings should not be use-d to seal flaws which are large enough to indicate a potential problem with weld integrity, but that the flaw size should be large enough to achieve some gain in tank testing productivity, i.e., it will improve productivity if tank testers do not have to identify and seal very small flaws which can be adequately sealed by the coating. As for weld integrity, pinhole-size flaws of approximately 10 roils in diameter and smaller do not represent significant weld defects. It is also recognized that tank tightness testing is not a check for weld integrity, but that weld integrity is established by a separate survey.

As already noted, the maximum hole size was set by a desire to improve productivity in tank tightness testing. If tank testing productivity can be improved without compromising personnel safeq or ship reliability, then a substantial improvement in overall ship building productivity can be achieved. In our-previous tank testing project (Reference 1) it was . established that a hydrostatic or air and soap test can detect leaks characterized by a 2 mil diameter hole. It was also established that, using ultrasonic methods, holes on the order of 7 roils in diameter could be detected. Thus, if the use of ultrasonics is to be appropriate for tank

tightness testing, then holes less than or equal to 7 roils in diameter must be sealed by the coating. Because the use of ultrasonics for leak detection appears to offer potential for improving productivity in tank tightness testing, we chose to set the minimum flaw size which must be sealed by the coating at 10 roils in diameter. Thus, if the tests conducted in this project demonstrate that coatings are effective for sealing flaws of this size for the life of the coating (and if this is substantiated in future trials on actual ship tanks) then ultrasonic detection techniques may effectively replace standard detection methods now in use with a substantial improvement in tank testing productivity.

2. Seal Strength

As shown in Section I, previous tests of the flaw sealing capability of coatings demonstrated that coatings effectively seal flaws at pressures up to 250 psig. Further, the holes sealed were much larger than the 10 mil diameter hole set as the maximum hole size which must be sealed by coatings evaluated in this study. The coatings were not checked for pressures higher than 150 psi. In a deep tank containing heavy liquid, hydrostatic pressures can reach 40 to 50 psi. In addition, dynamic effects could increase the pressure levels even higher; however, it is extremely doubtful the pressures would ever exceed 150 psi. Because the earlier tests demonstrated that coatings did not break down at pressures up to 150 psi, we chose to limit test pressures in this study to 50 psig. This is the maximum pressure considered safe for air-testing in our test fixture.

3. Longevity of the Coating

Longevity was established by considering normal coating life, which, in ship tanks, is generally about 10 years. So long as the coating is effective in protecting the tank and preventing tank corrosion, it should also be an effective seal for flaws of 10 roils in diameter and less. To establish the durability of the coatings, accelerated aging tests were conducted which represented service conditions of 6 months to 20 years. During the aging process intermediate tests were conducted to determine the effect of aging on the seal. Ideally, the seal should remain indefinitely even though the coating itself deteriorates. Aging tests were extended to 20 years And coatings were tested in severe (“not recommended”) environments to see if this was indeed the case.

B. Establish Regulator Coating Performance Criteria

The American Bureau of Shipping (ABS) was contacted regarding the use of coatings to seal small flaws in integral ship tanks. Specifically, we wanted to identify the data which ABS would require from our tests in order for them to permit the use of coatings to seal small weeps or flaws in integral ship tanks. To obtain this information, a letter was sent to ABS which stated our objectives, emphasized the effectiveness of coatings in sealing small flaws, and proposed possible rule changes to tank testing procedures if coating durability is found to be adequate in accelerated aging tests. A copy of this letter is included in Appendix A.

As a result of this inquiry, a meeting was scheduled between ABS, SWRI, and L. D. Chirillo Associates. At the meeting, ABS'S positive and negative viewpoints toward the use of coatings for sealing small flaws or weeps in shiptanks were identified. The positive aspects are:

- The possibility of improved scheduling flexibility for AES surveyors during tank tightness testing through the use of ultrasonic detectors. Scheduling flexibility is improved because there is no soap solution to dry out.
- ABS would like the use of ultrasonics for tightness testing dermmstrated in the shipyard.
- ABS sees a possibility for immediate application of ultrasonic detection to bulkheads separating common cargos. Small flaws, which might possibly go undetected with ultrasonics, would not be detrimental.

The negative aspects which were identified regarding the use of coatings for sealing small flaws were:

- From-ABS's viewpoint, the effectiveness and durability of the coating to seal small .weeps has not been established.
- Coatings have not been accepted in the past for sealing weld flaws.

- Permitting flaws to be sealed with coatings may promote a reduced level of workmanship.
- Tank testers may allow larger than desirable leaks to pass inspection, expecting them to be sealed by the coatings.

ABS is currently unwilling to accept coatings for sealing flaws in critical boundaries; that is, boundaries separating uncommon cargos or cargos from ballast tanks, etc. They did not propose a criteria which if met could lead to acceptance of coatings for sealing flaws in these boundaries. Again the positive aspects are that ABS is considering the use of ultrasonics for non-critical boundaries if ultrasonic leak detection is found.to be viable in the shipyard. If ultrasonics are found to be viable for tank testing in the shipyard environment, then it offers possibilities for checking certain parts of the tank structure at the block stage. The use of ultrasonics at the block stage, as well as at the completion stage (in lieu of a soap and air solution), would further improve productivity above-current levels. Shipyard evaluations were not within the scope of work of this contract, but can be evaluated in future investigations.

IV. LABORATORY EVALUATIONS

Specimen Preparation

One hundred and forty eight test specimens were prepared to evaluate the leak sealing capabilities of the coatings. As shown in Figure 4, each of the specimens was fabricated from a 6" x 6" square.of l/4-inch steel plate. A 3/4-inch hole was drilled at the center of each square and capped by a 2" x 3" piece of 1/4" steel welded to the base plate. The two pieces of l/4-inch steel were separated by brass shims which did not interfere with the passage of air or moisture through the 3/4-inch hole. The welds were purposefully made in such a way as to produce a number of weld flaws. In addition to the weld flaws , a series of small holes were drilled in the base plate. These holes were arranged so that when the specimen was half submerged in a solution, half of the holes were in the liquid phase and half in the vapor phase. A typical specimen had two each of 7, 10, 16, 20 and 31 mil diameter holes. These holes were added, in addition to the weld flaws, so that the coatings could be evaluated for flaws of known size.

After the welding and drilling operations were complete, each specimen was tested with an air and soap solution at pressures up to 50 psig to identify all leaks. Subsequent to the leak identification, each specimen was sandblasted with coarse sand to a steel profile of 3 to 4 roils. They were then cleansed in an ultrasonic bath of trichlorethylene and rinsed . with water. After cleaning and rinsing, the specimens, particularly the holes and weld region, were cleared of water by high pressure air and allowed to air dry. Coatings were then applied-by conventional air spray using the nozzle size recommended in the technical data sheets. Each coat of paint was applied in the thickness and sequence recommended by the manufacturer, and both wet and dry film thickness readings were taken. Mr. Dick Vaughan of Sigma Coatings visited SWRI during the specimen preparation. He demonstrated the use of both wet and dry film thickness measurements and offered suggestions on the coating applications. A number of dummy specimens were coated, following the manufacturer's directions, to "perfect" the spraying techniques before the actual test specimens were coated. Table XII summarizes the preparation of the test specimens.

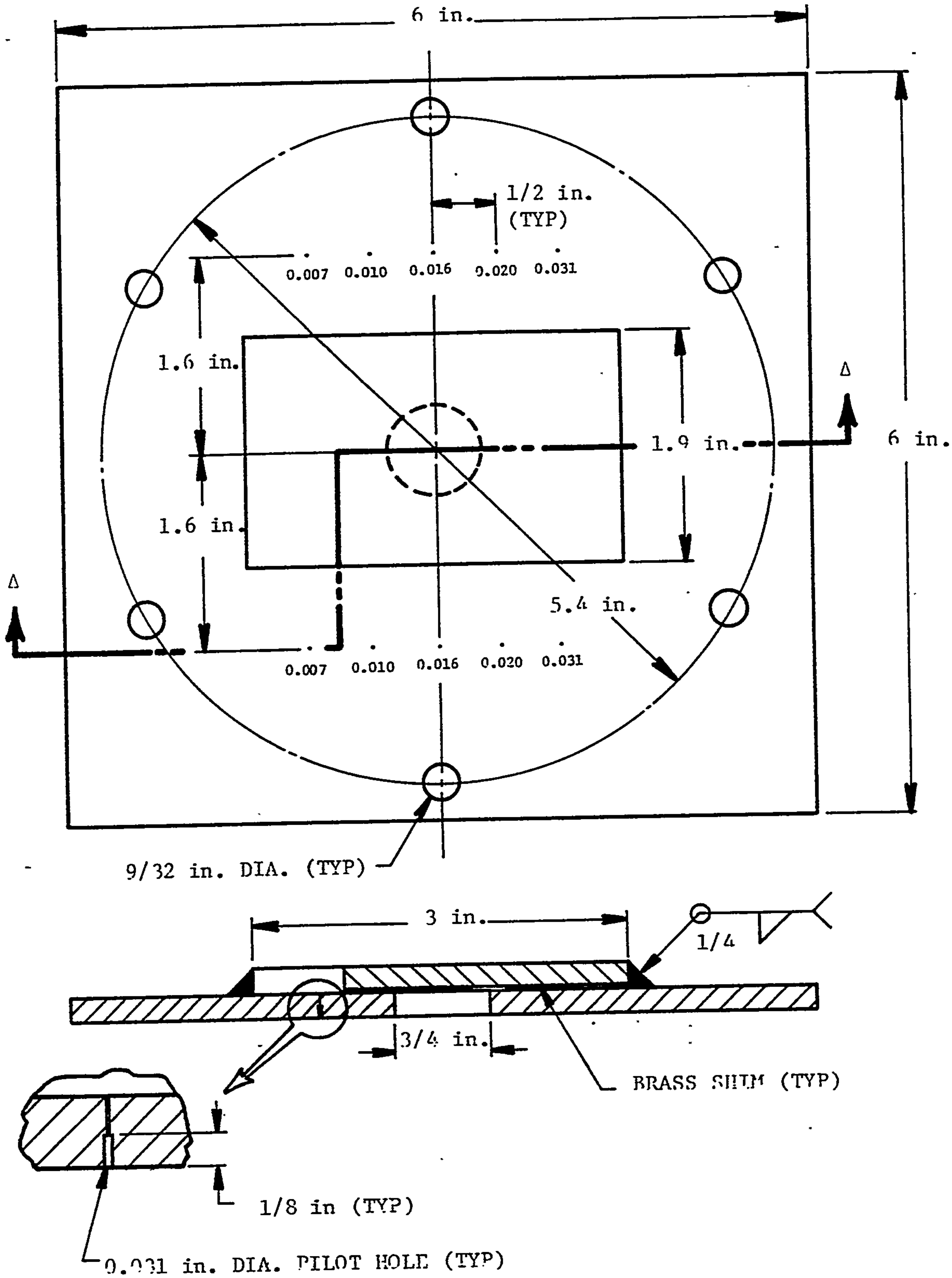


FIGURE 4. TEST SPECIMEN USED FOR COATING EVALUATION

TABLE XII. TEST SPECIMEN CHARACTERISTICS

- Fabricated 148 test specimens
  - Made from l/4-inch mild steel plating
  - Contained holes of known diameter (7 roils to 31 roils)
  - Contained fillet weld flaws
  - Weld flaw identification was made using air and soap at 50 psig
- Specimens were sandblasted with coarse sand to a steel profile of 3-4 roils
- Specimens were cleaned in ultrasonic bath of trichloro-ethylene and water rinsed
- Water was cleared from holes and weld flaws with high pressure air and specimens were air dried "
- Coatings were applied with conventional spray equipment according to the manufacturer's specifications
  - Weldments and drilled holes were stripe coated in two-thirds of the specimens
  - One-third of the specimens were not stripe coated

As noted in Section 11, of the coatings listed in Table VIII, nine were applied to the steel specimens for the sealing and aging tests. Typically, fifteen specimens were painted with each coating system, and of these, ten were stripe coated and five were not. All except four of the 148 test specimens were coated at SWRI. These four specimens were sent to the International Paint Company for final sandblasting and application- of the coating. . These specimens were coated with Matcote Matstick - 107 to a thickness of 1/8 - 1/4 inch and then topcoated with International's Interguard TAA and EXA Series coatings to a thickness of 4 roils and 5 roils (dry), respectively. The Matstick 107 is an epoxy coating reinforced with glass fibers. The coating was developed to seal large flaws in in-land tanks.

B. Small Flaw Seal Tests

After test specimens were coated, each one was again tested to locate unsealed holes and weld flaws. Out of the 148 specimens tested, 2154 leaks existed before-the coatings were applied and 67 remained after coating. It is important to note the effectiveness of the coatings for sealing the weld flaws and the drilled holes in the test specimens. This information is summarized in Table XIII. The data have been grouped into stripe coated and non-stripe coated specimens and by weld flaws and drilled holes. Givep in the table are the total number of plates tested in each of the categories, the number of leaks'found prior to coating, the number of holes found after coating, and the percentage of leaks sealed. The minimum efficiency of the coating was 92.77% and that was for non-stripe coated drilled holes. It is important to note that stripe coating the drilled holes sealed 99.90% of them. This table does not indicate the size of the holes that were not sealed by the coatings. This is shown for the drilled holes in Table XIV. As the data in Table XIV show, all holes 10 tils in diameter and below.were sealed in both the stripe coated and non-stripe coated specimens. Also, all but one 31 mil diameter hole were sealed in the stripe coated specimens. Because we were unable to quantify the size of the weld flaws, no similar data can be cited; however, it is safe to assume that the effectiveness of the coatings is similar for both the drilled holes and weld flaws. Thus, we believe that these tests have shown the effectiveness of the coatings to initially seal small flaws.

TABLE XIII. THE LEAK SEALING EFFICIENCY OF COATINGS - ALL FLAW SIZES

Coating Application	Type of "Flaw	Number of Plates Tested	Number of Leaks Prior to Coating	Number of leaks After Coating	% of Leaks Sealed by,the Coatings
Stripe Coated	Weld Flaws	100	500	18	96.40
	Drilled Holes	100	956	1	99.90
Not Stripe Coated	Weld Flaws	48	228	15	93042
	Drilled Holes	48	470	34	92.77

TABLE XIV. LEAK SEALING EFFICIENCY OF THE COATINGS FOR DIFFERENT SIZE HOLES

Coating Application	Hole Diameter (in.)	Number of Leaks Prior to Coating	Number of Leaks After Coating	% of Leaks Sealed by the Coatings
Stripe Coated	.007	156	0	100.00
	.010	200	0	100.00
	.016	200	0	100.00
	.020	200	0	100.00
	.031	200	1	99.50
Not Stripe Coated	.007	86	0	100.00
	.010	96	0	100.00
	.016	96	2	97.92
	.020	96	8	91.67
	.031	96	24	75.00

Simulated in-senrice aging tests, conducted as described in the next section, determine the durability of the seal after the coatings have been exposed to in-service conditions.

C. Seal Life Tests

A series of accelerated agin tests were developed to determine the endurance of the coatings over a service life of up to twenty years. As noted in Section 11.C, three different cargos were selected for these tests, and these cargos were chosen because they are known to be detrimental to tank coating systems. The cargos chosen were salt water, methanol alternated with distilled water, and jet fuel. In each of these tests, each specimen was positioned so that one half was submerged in the solution and one half was exposed to the vapor phase. In order to accelerate the aging process all tests were conducted at elevated temperatures relative to the normal in-service temperature, and this permitted short periods of testing to represent longer periods of exposure in setice.

The accelerated aging tests were conducted within the thermal limits of polymer durability; that is, always at a test temperature below the decomposition temperature of the coatings and usually below the maximum recommended service temperature. Test times were based on principles of physical chemistry which are related to the Arrhenius activation equation. These principals stem from the fact that nmst chemical reactions proceed at rates which increase 10% to 20% for each 1°C rise in temperature. The lower limit, a 10% increase per l“C, was chosen for these tests. This approximately doubles the reaction rate with each 10°C increase in temperature. This relationship has been verified for polymers and other materials by the roofing industry, polymer manufacturers: and coating manufacturers [81]. “

Three tests were formulated, one for each of the three cargo types. The tests were conducted at different temperatures and for different durations. Generally, test temperatures were set at the vapor pressure of the liquids at one atmosphere. However, the availability of a steam retort system at SWRI permitted operation of the salt water test at 250°F and 14 psig pressure. Test procedures are given in the following paragraphs.

:,

1. **Salt Water Test**

The salt water test was conducted at 250″F for a duration of 21 days. Specimens were placed in a covered container (but not sealed) and each specimen was submerged halfway in a 4% salt water solution. The covered containers were placed in a steam retort (Figure 5) which maintained a constant temperature of 250″F at 100% relative humidity. The specimens were inspected weekly for deterioration and one series of specimens was leak tested after 10 days. Otherwise, the specimens were undisturbed.

2. **Methanol/Water Test.**

The specimens were exposed to alternating solutions of methanol "and distilled water at 150″F for 28 days. Exposure was started with methanol for one week and alternated with water at one week intervals. To change from methanol to water and vice versa required about one hour. During this time some air drying of the specimens did occur. As in the salt water test, specimens were placed in the solutions so that one half of each. specimen was submerged and one half was in the vapor phase. The vapor phase was maintained at 100% relative humidity. A view of this test setup is shown in Figure 6.

3. **Light Fuel Oil Test_**

These tests were also conducted at 150°F which is approximately the vapor pressure of JP-4 at 14 psia. As with the salt water and methanol/ water tests, each specimen was placed in the JP-4 with one half submerged in the fluid and one half in the vapor phase. These tests were continued for seven days. A close-up view of this test setup is given in Figure 7.

Based upon the "relationship that the degradation of the coatings accelerates by a factor of two for every 10°C change in temperature, the simulated senice.life of the three tests can be estimated. On the assumption that the mean operating temperature, or mean service temperature for the coatings is 75°F, the following estimates for simulated service life were

o Salt water test at 250°F for 21 days = 20 years for simulated service life.

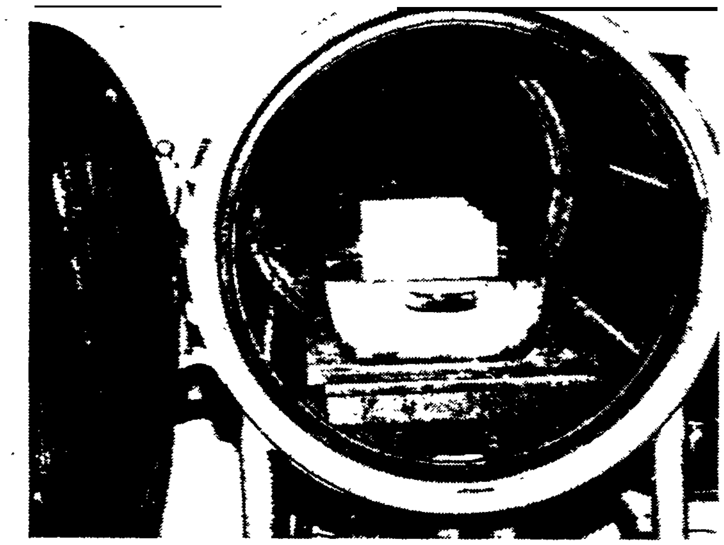


FIGURE 5. SALT WATER TEST RETORT
(CONTAINER COVER REMOVED)

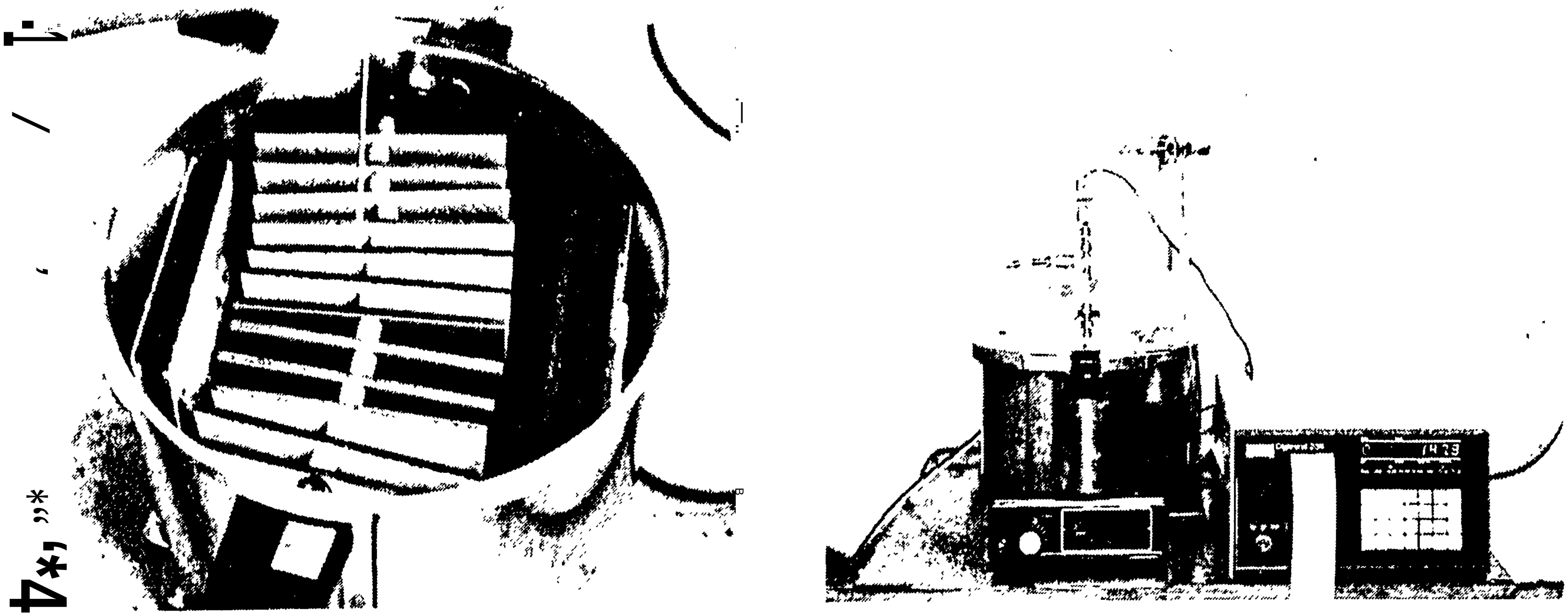


FIGURE 6. SETUP FOR METHANOL/WATER TESTS

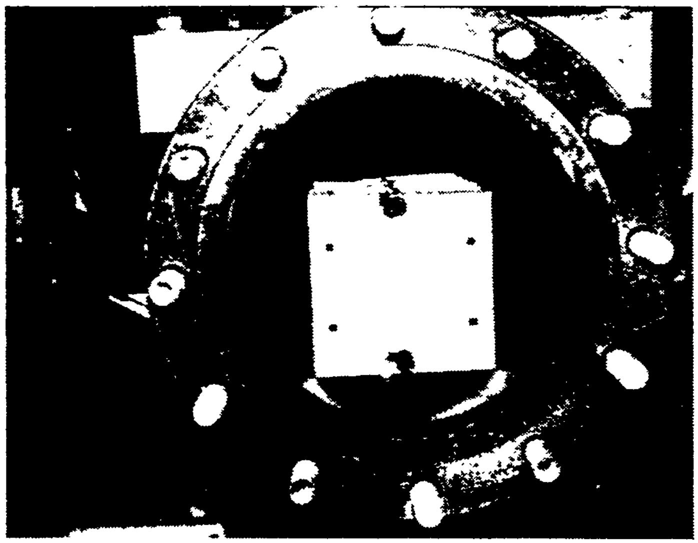


FIGURE 7. CHAMBER AND TEST SPECIMENS FOR JP-4 TESTS

o Fuel oil test at 150°F for 7 days = 6 months simulated service life.

o Methanol/Water test at 150″F for 28 days = 2 years simulated service life.

There is a considerable variation in the simulated setice life of the three tests; this was caused primarily by the desire to test at or near atmospheric pressure which limited the temperatures in the methanol and JP-4 tests. A retort was available for the salt water test which permitted a higher temperature and above atmospheric pressure. It was observed, as will be noted in the next section, that in the salt water test those coatings which were adversely affected by the salt water started to deteriorate very quickly. Those which were not affected continued to perform well. Thus it is our belief that even-though the methanol/water and JP-4 tests were of, shorter duration, deterioration of susceptible coatings will begin very early and, thus, will show up during the tests.

A summary of the aging tests performed on the ten different coating systems is summarized in Table XV. It also identifies which coatings were specifically recommended for the different environments and which were not. Note that the methanol/water test is a very severe environment and this type of service was not recommended by any of the coating manufacturers. Some coatings were subjected to all three tests to determine whether or not the coatings vere able to seal small flaws even after substantial breakdo~m of the coatings had occurred.

D. Results of the Seal Life Tests

After aging, the coatings were evaluated visually and by repeating the leak tests which were performed before the coatings were aged. In general, the visual observations and test results agree, i.e., more leaks were observed in coatings which showed the most visible deterioration.

1. Coating Deterioration

Visual examinations of the specimens were made at approximately one week intervals during the aging tests. Brief descriptions of the effects of the aging on the coatings at the end of each test are given in

TABLE XV. SUMMARY OF AGING TESTS

Coating Generic Name	Coating Trade Name	Environments		
		Salt Water	Methanol/ Water	J-P-4
Polyamide Epoxy	Amercoat 81/82	C	0	0
	Carboline 191	8		0
Phenolic Apow	Phenoline 373	0	0	0
Ketimine Epoxy	Intergard TAA 423 HS	0	0	0
	Intergard TAA over Matstick 107	0		0
	Intergard EXA over Matstick 107	0		0
Amine Cured Epoxy	Amercoat 395	0	0	0
	Carboline 187	0		0
	Hempel 1540	0	0	0
	Hempel 1580/3544			Q
Epoxy - Coal Tar	Carbomastic 14	8	0	0-

0 Tested in ‘lreco~ended$t environment as determined from the manufacturers resistance guide.

O Tested in "non-recommended" environment.

* Recommended for up to 30 days continuously in methanol. Not recommended for alternating methanol and water without complete drying between cargos.

Table B.1 (Appendix B). Although the coating breakdown was progressive, the most obvious visible changes occurred very early in the aging tests. Coating breakdown is described as

- none
- slight
- moderate
- some corrosion debonding
- severe
- very severe

Examples of these levels and types of coating breakdown-are shown in Figure 8. Parts (a), (b), (d) and (e) are for the same coating and show results produced by the different environments and for different specimens in the same environment. Parts (c) and (f) show deterioration for another coating. Severe or very severe coating breakdown did not occur for any coatings which were exposed to their recommended service environment. The other types of breakdown did occur in some of the "recommended" coatings. As Table B.I also shows, some coatings showed no visual damage when tested in environments for which they were not recommended.

Because all coatings.varied in their appearance, a verbal description of the degree of coating breakdown is given below. These descriptions compliment the photographs in Figure 8 to better define the deterioration of the coatings produced by the aging.

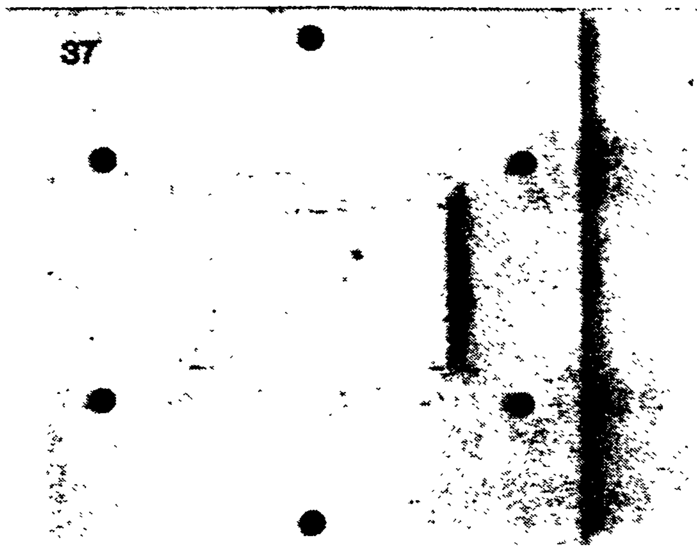
none - only slight discoloration permitted

Slight- mild discoloration and minor penetration as evidenced by rust stains - no obvious debonding

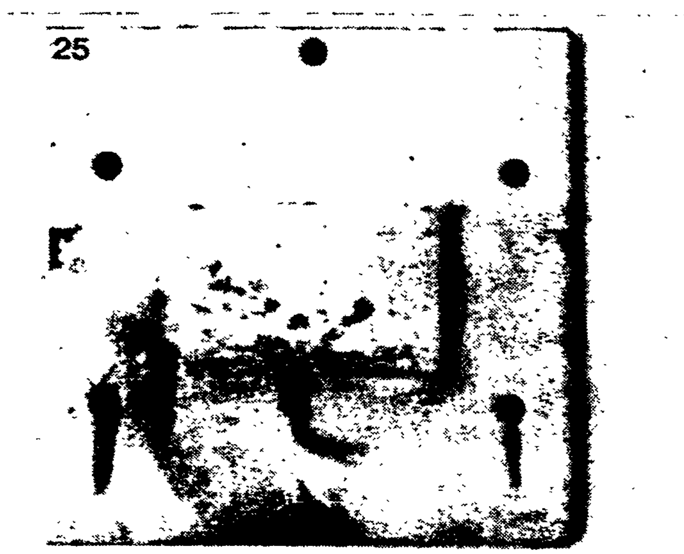
moderate - substantial discoloration and moderate penetration as evidenced by rust stains - no obvious debonding

corrosion debonding - moderate deterioration plus minor debonding produced by liquid penetration, chemical breakdown of the coating and/or substrate corrosion.

severe - moderate deterioration plus obvious debonding of coating to prime coat or substrate produced by liquid penetration, chemical breakdown of the coating and/or substrate corrosion.

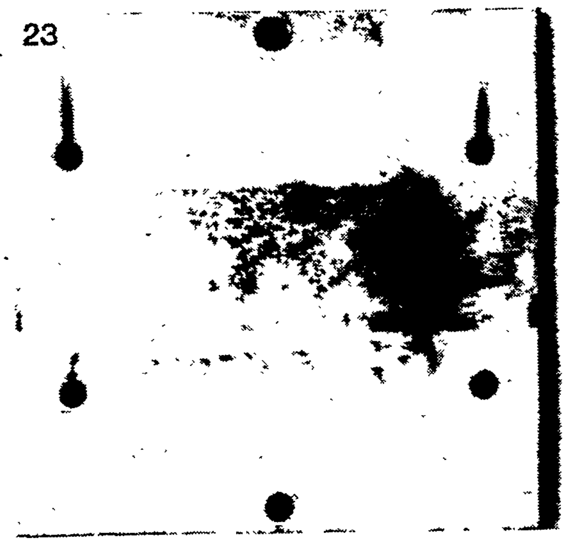


(a) none



(b) slight

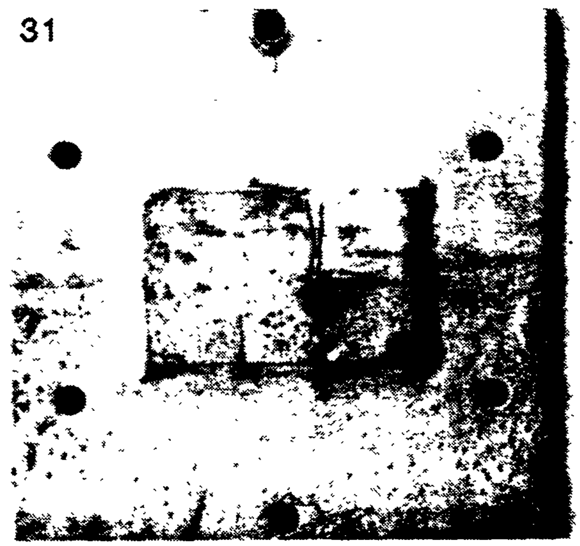
FIGURE 8. EXAMPLES OF COATING BREAKDOWN DURING THE AGING TESTS (continued)



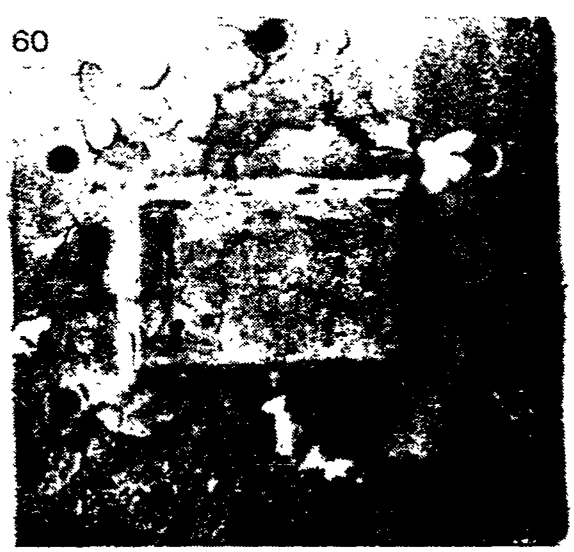
(c) moderate

(d) corrosion debonding

FIGURE 8. EXAMPLES OF COATING BREAKDOWN DURING THE AGING TESTS (continued)



(e) severe



(f) very severe

FIGURE 8. EXAMPLES OF COATING BREAKDOWN DURING THE AGING TESTS (concluded)

very severe - wide spread and complete coating breakdown" produced by liquid penetration, chemical breakdown of the coating and/or substrate corrosion.

Coating breakdown did not always correlate with leakage as can be observed in Table B.I (although "this was generally true). In some cases of severe corrosion debonding, the flaws remained sealed because corrosion did not penetrate into the holes which were partially filled with the coating. This will be clearly shown in Part 3 of this section.

2. Leak Tests

Results of the leak tests on the individual specimens are also included in Table B.I (Appendix B) under the heading "Number After Aging." These data are further summarized in Tables B.II, B.111 and B.IV, which show the number of leaks before and after aging for the three different environmental tests. Note that all results for the weld flaws are grouped together because weld flaw size could not be measured easily. Results for the drilled holes are given by hole size.

As shown in Table XV of Section IV.C, results for salt water and JP-4 contain data for both "recommended" and "ncn-recommended" coatings. A more appropriate measure of coating performance is found by examining the results for "recommended" coatings because, in service, coatings will always be matched to the cargos. These results are given in Table XVI. Note that for *the* striped coated specimens all of the weld flaws (100%) were sealed and only four of the holes opened up giving a 99% effective seal for the 398 holes that were initially sealed. For holes 0.010 inches in diameter and smaller, the coating was effective for 99.4% of the leaks. In the specimens which were not stripe coated all of the holes (100%) and 97% of the welds remained sealed after aging. The important aspect of these results is that for holes 0.010 inches in diameter and smaller, the coatings were effective, after aging, 99.6% of the time. This result is obtained by combining results for both stripe coated and non-stripe coated specimens. Similar results obviously can be expected for weld flaws of similar size since 100% of the sealed flaws for the stripe coated specimens remained sealed after aging.

TABLE XVI. RESULTS OF AGING TESTS ON COATINGS WHICH WERE RECOMMENDED FOR THE TEST FLUID

Coating Application	Type of Flaw	Number of Leaks Before Coating	Number of Leaks After Coating	Number of Leaks After Aging
Stripe Coated	Weld Flaws (all)	205	6	6
	Drilled Holes:			
	0.007 in.	72	0	0
	0.010 in.	82	0	1
	0.016 in.	82	0	0
	0.020 in.	82	0	0
	0.031 in.	82	2	5
Not Stripe Coated	Weld Flaws (all)	142	7	11
	Drilled Holes:			
	0.007 in.	56	0	0
	0.010 in.	56	0	0
	0.016 in.	56	1	1
	0.020 in.	56	2	2
	0.031 in.	56	7	7

Results for coatings which were tested in "non-recommended" environments are given in Table XVII. As can be seen in Table XV, these results are principally from the methanol/water tests but also include two specimens each from the salt water and JP-4 tests. These test results are not characteristic of what should occur in ships, because in-service the coatings are always matched to the cargo; however, these results should be indicative of the worst performance which could be expected after severe coating deterioration from any cause.

In these tests, the effectiveness of the coatings (both striped and non-striped) for sealing 0.010 inch diameter and smaller holes was 98% (3 leaks out of 152 sealed holes). This performance is very good for coatings which-were tested in "non-recommended" cargos. For all weld flaws and drilled holes the coating effectiveness was (not counting the 3 leaks that apparently rusted closed) 95.4%.

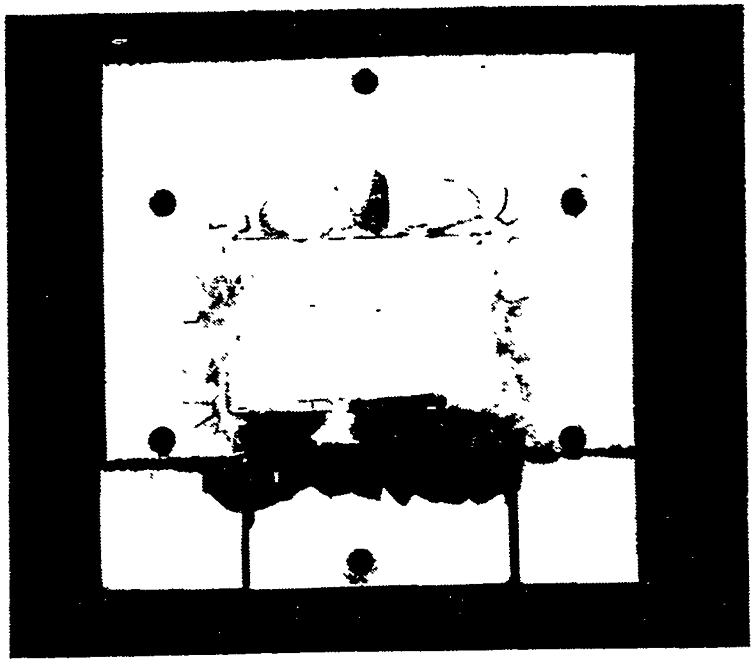
It is interesting to note from the results in Table XVII that the coatings which were applied <u>without</u> the stripe coat performed better than the ones which were applied <u>with</u> the stripe coat. One explanation for this is that the spray coat penetrates the flaws better than the stripe coat. In the stripe coated specimens the first coat over the flaws is a brush coat. In the non-stripe coated specimen the first coat is a spray coat. This explanation is partially supported by viewing sections through the drilled holes as described in the next section. Holes were plugged in one specimen in which the coating completely separated from the surface of the substrate by corrosion debonding.

3. <u>Specimen Sectioning</u>

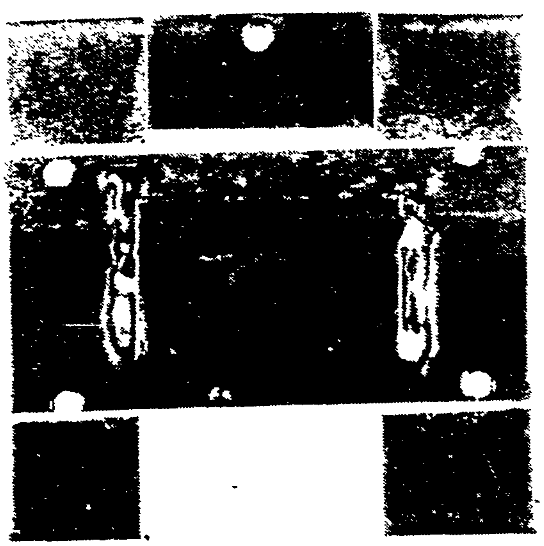
Specimens, which had been aged in salt water, were sectioned through the drilled holes to see how the holes were being plugged by the coatings. Two different coating systems were examined, both of which effectively sealed the drilled holes. One coating system (Specimen 76 in Table B.1) showed very little deterioration from the aging, and the other coating system (Specimen 43 in Table B.1) showed extensive corrosion debonding. Photographs of these specimens after sectioning are shown in Figure 9. All of the coating has debonded at the location of one row of

TABLE XVII. RESULTS OF AGING TESTS ON COATINGS WHICH WERE NOT RECOMMENDED FOR THE TEST FLUID

Coating Application	Type of Flaw	Number of Leaks Before Coating	Number of Leaks After Coating	Number of Leaks After Aging
Stripe Coated	Weld Flaws (all)	149	10	21
	Drilled Holes:			
	0.007 in.	58	0	2
	0.010 in.	58	0	1
	0.016 in.	58	0	3
	0.020 in.	58	0	5
	0.031 in.	58	0	4
Not Stripe Coated	Weld Flaws (all)	36	5	4
	Drilled Holes:			
	0.007 in.	18	0	0
	0.010 in.	18	0	0
	0.016 in.	18	0	0
	0.020 in.	18	0	0
	0.031 in.	18	4	2



(a) Specimen with severe corrosion debonding



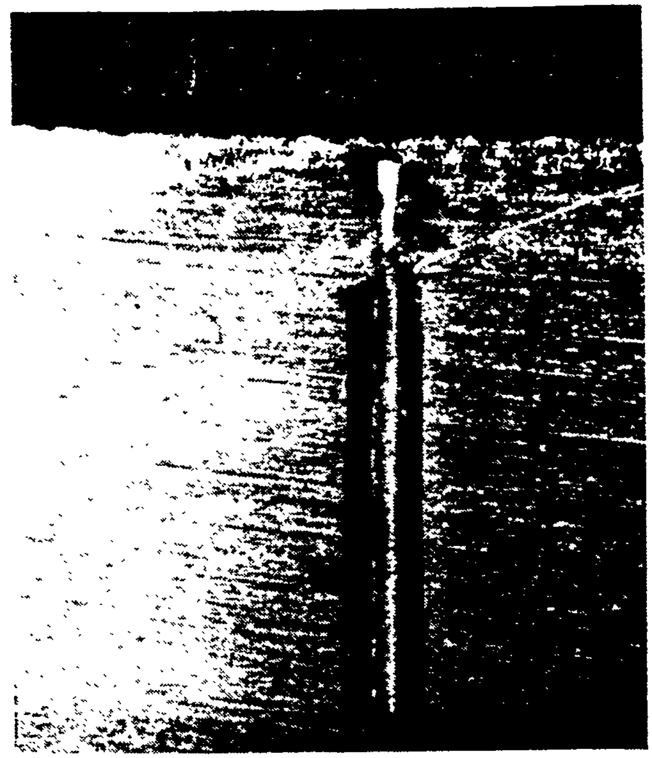
(b) Specimen with no deterioration

FIGURE 9. SPECIMENS SECTIONED THROUGH THE DRILLED HOLES

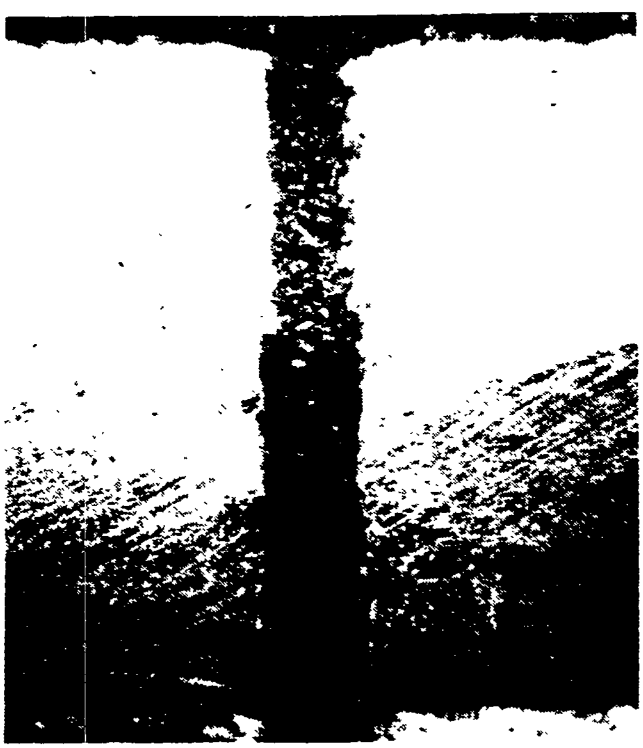
drilled holes as shown in part (a) of the figure. It wss at this location that the section was taken. No obvious breakdown of the other coating occurred

Sections through the specimens are shown in Figure 10. Parts (a) and (b) are for the specimen with severe corrosion debonding. Note that the coating penetrated well into the hole and the seal remained effective even after the surface protection had failed. Parts (c) and (d) show sections for the coating that did not deteriorate from the aging. T%is coating was very viscous and did not penetrate the smallest hole; however, because the coating system was recommended for and withstood the environment very well, the seal was maintained. Thus, even though some of the coatings tested penetrated well into the flaws, a special coating could perhaps be developed for leak sealing which penetrates even better than existing coatings. This coating. could be applied as a general base coat or just as a stripe coat.

(a) 0.031 in. diameter hole



(b) 0.007 in. diameter hole



(c) 0.020 in. diameter hole

(d) 0.007 in. diameter hole

FIGURE 10. SECTIONS THROUGH THE HOLES OF SPECIMENS IN FIGURE 8

V. LABORATORY EVALUATION OF ULTRASONIC LEAK DETECTORS

The final segment of our laboratory work concentrated on obtaining additional performance data on ultrasonic detectors for this specific application. The testing included an evaluation of the relative performance of two different detectors, a comparison of the relative sensitivity of an ultrasonic detector for detecting small flaws as compared to the air and soap method of detection, an evaluation of the use of an ultrasound generator to enhance the sensitivity of the ultrasonic detection method, and the effects of extraneous noises common in a shipyard environment on the ultrasonic detection method. For this evaluation, two detectors, considered to be representative of the state-of-the-art, were used. They were a Techsonics, Inc. Model 112 Son-Tector Ultrasonic Detector and a Hewlett-Packard, Inc. Model 4918A Ultrasonic Detector. Both units are battery powered and portable. Typical performance data for these units are shown on Figure 11. The ultrasound generator used for these laboratory tests was a Techsonics, Inc. Soncaster II-S.

For the first portion of the evaluation, the two detectors were used to detect a 7 mil diameter hole in a quarter inch thick steel plate. Various air overpressures were used to determine from what distance the hole could be detected by the ultrasonic sensors. It was found that the performance of the Techsonics and Hewlett-Packard units was virtually identical. The units both detected the hole when the differential air pressure was set at 2 psig. The detectors could locate the hole from a maximum distance of approximately one foot with the 2 psig air pressure. The maximum distance from the plate at which the detectors could locate the hole increased linearly as the pressure increased.

The test procedure was then repeated with the test setup modified slightly. An ultrasound generator was placed on the opposite side of the

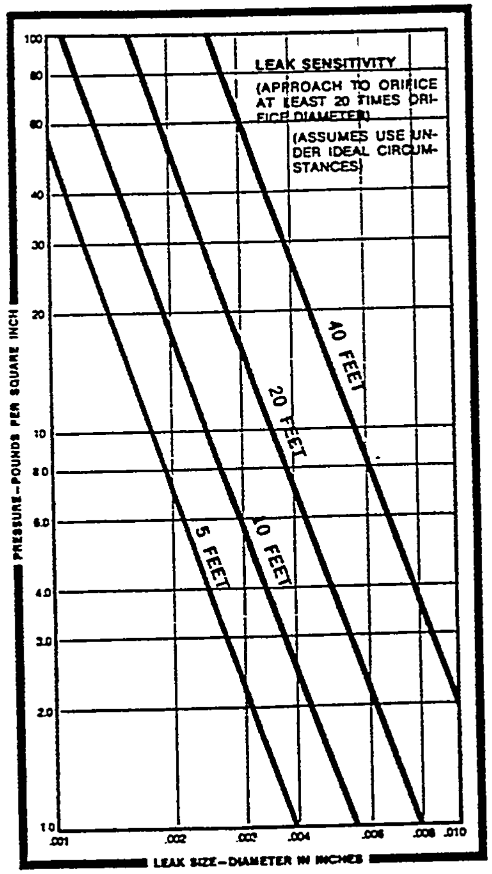


FIGURE 11. TYPICAL ULTRASONIC DETECTOR SENSITIVITY

noise generated by the air passing through the test hole. With this setup, the maximum distance from the hole at which the detectors could locate the hole increased by between 10 and 15%. These results indicate that it may be beneficial to use an ultrasound generator to supplement the ultrasonic noise generated by the air passing through flaws in the tank boundary. The power requirements for a noise generator which could produce a significant improvement in detection sensitivity was not established.

As a comparison between the ultrasonic detection test and a standard air and soap test, two aged, coated specimens were rechecked for leaks. The two specimens were both severely deteriorated by the aging. A total of nine weld flaw leaks were detected by the air and soap test after aging. The differential air pressure required to detect the flaws with a soap solution was between 10 and 50 psig. However, all nine holes were located with the ultrasonic detector with a 2 psig differential air pressure and an ultrasound generator located on the opposite side of the specimens from the detector. This means that the standard 2 psig air and soap test detected no flaws while a standard ultrasonic test located nine flaws; indicating the ultrasonic test was the more sensitive of the two tests. Again, these tests were performed in a small tank with the sound generator close to the flaw. The sound generator requirements necessary to achieve such an improvement in a ship tank were not established.

As a final test of the ultrasonic detectors, &he units were tested with other activities occurring near the detection testing area. Electric welding, slag chipping, and grinding on a steel pipe were being done approximately 15 feet from the location where the ultrasonic detection tests were being conducted. The detectors were locating the 7 mil holes used for the other portions of this evaluation. The detectors were within a distance of three feet from the test hole. It was found that the welding and grinding interfered with the detectors. The interference was strong enough to prevent the detection of the hole location. However; both

VI. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

o Coatings can seal holes up to 0.160 inch in diameter at pressures up to 150 psig.

0 Flaws sealed by the coatings remain sealed after twenty years of simulated in-service aging.

0 Flaws remain sealed even after severe surface deterioration (corrosion) has occurred.

0 Laboratory aging tests show that coatings tested in their recommended service environment seal small holes (10 mil diameter and smaller) 99.6% of the time.

0 Laboratory aging tests show that coatings tested in environments for which they are not recommended seal small holes- (10 mil diameter and smaller) 98% of the time.

0 ABS does not routinely permit the use of coatings for sealing small flaws in ship tanks.

0 ABS does not now accept the use of ultrasonic detection as a viable method for ship tank tightness testing.

0 ABS is willing to support shipyard evaluations of ultrasonic detection methods for tank tightness testing.

0 ABS is also willing to support, on an experimental basis, an in-service evaluation of the effectiveness of coatings for sealing small leaks in ship tanks.

0 Ultrasonic leak detection sensitivity is improved by placing ultrasound generators in the pressurized tank.

0 The combination of low pressure air and ultrasound makes the

B. **Recommendations**

- Shipyard evaluations of ultrasonic leak detection methods for tank tightness testing are recommended.
- It is recommended that ultrasonic leak detection methods for tank tightness testing be accepted, on a trial basis, for the tightness testing of selected ship tanks.
- Long term in-service evaluations of coatings to determine their effectiveness for sealing small leaks (below the practical detection limits for ultrasonics) should be performed.
- Stripe coating of all weld seams is recommended to improve tank tightness.
- It is recommended that an investigation be conducted to determine the feasibility of developing a special sealing primer to be used for stripe coating of weld seams in ship tanks.

REFERENCES

1. Cox, P. A., E. B. Bowles, and R. L. Bass, "Improved Tank Testing Methods," Todd Shipyards Corp., SwRI Project No. 02-4890, Final Report, January 1980.

2. Fink-Jensen, P., "Hardness Testing of Organic Coatings", Pure and Applied Chemistry, Vol 10, 1965, pp 240-292.

3. Bickerman, J. J., "Causes of Poor Adhesion - Weak Boundary Layers", Industrial and Engineering Chemistry, Vol 59, No. 9, September 1957, pp 40-44.

4. Schonhorn, H. and F. W. Ryan, "The Effect of Polymer Surface Morphology on Adhesion and Adhesive Joint Strengths", Advances in Chemistry Series, No. 87, 1968, pp 140-153.

5. Asbeck, W. K., "Measuring the Adhesion of Coatings", Journal of Paint Technology, Vol 43, No. 556, May 1971, pp 84-91.

6. van Laar, J. A. W., "The Durability of Paint Coatings - Pt. 1", Corrosion Prevention and Control, Vol 8, December 1961, pp 32-42.

7. Mueller, F. X. and D. M. Olsson, "Application of Statistical Designs for the Solution of Industrial Finishing Problems", Journal of Paint Technology, Vol 43, No. 556, May 1971, pp 54-62.

8. Phillips, G., "The Physical Behavior of Paint Films", Journal, Oil and Colour Chemists' Association, Vol 44, September 1961, pp 575-595.

9. May, W. D., N. D. P. Smith, and C. I. Snow, "The Adhesion of Surface Coatings", Transactions, Institute for Metal Finishing, Vol 34, 1957, pp 369-386.

10. Joint Services Committee on Paints and Varnishes, "An Investigation Into a Method of Test for Assessing the Adhesion of Paint Coatings", Journal, Oil and Colour Chemists' Association, Vol 46, April 1963, pp 276-300.

11. Bullett, T. R. and J. L. Prosser, "Paint Adhesion and the Metal Surface", Transactions, Institute for Metal Finishing, Vol 41, 1964, pp 112-120.

12. Walker, P., "The Effect of Water on the Adhesion of Surface Coatings," Official Digest, Journal of Paint Technology, Vol 37

14. Holloway, M. W. and P. A. Walker, "A Method for the Measurement of the Adhesion of Surface Coatings Under Service Conditions", Journal, Oil and Colour Chemists' Association, Vol 47, October 1964, pp 812-823.

15. Pascoe, M. W., "The Problems of Adhesion in the Paint Industry", Aspects of Adhesion-3, A3.ner, D. J., cd., University of London Press, London, 1967, pp 85-94.

16. Laesch, W. E., "Effects of Environment on Degradation of Paint Films", Official Digest, Federation of Paint and Varnish Production Clubs, vol 36, 1964, pp 686-694.

17. Jedlicka, W. W. and T. H. Geschke, "Rapid and Continuous Evaluation of Corrosion Using Extremely Thin Metal Substrates," Journal of Paint Technology, Vol 41, No539, December 1969, pp 680-686.

18. Gusman, S., "Studies of the Adhesion of Organic Coatings", Official Digest, Journal of Paint Technolom, vol 34, August 1972, pp 884-905.

19. Snow, C. I., "Some Principles of Testing Paints and Varnishes", Official Digest, Journal of Paint Technology, Vol 29, September 1957, pp 907-919.

20. Taylor, C. J. A. and S. Marks, eds. Paint Technology Manuals - Part 5. The Testing of Paints. New York: Reinhold Publishing Corp., 1965.

21. Sward, G. G., ed. Paint Testing Manual - Physical and Chemical Examination of Paints, Varnishes, Lacquers, and Colors. Lutemille-Timonium, MD, June 1972.

22. Bullett, T. R. and J. L. Prosser, Problems in Adhesion of Paints to Metals in Adhesion Fundamentals and Practice. London: McLaren and Sons, 1969.

23. Dunkley, F. G. and D. P. Earp, "The Correlation of Service Behavior of Paint," Journal, Oil and Colour Chemists' Association, Vol 44, 1961, p 649.

24. Blom, A. V., Organic Coatings in Theory and Practice. London: Cleaver-Hume Press, 1947.

25. Heaton, N. and C. Griffin, Outline of Paint Technology. London: Griffin and Co., 1956.

27. Banfield, T. A., "Protective Aspects of Marine Paints," Progress in Organic Coatings, VO1. 7, No. 3, Aug. 13, 1979, PP 253-277.

28. Zakhidov, R. A., "Accelerated Tests of Coatings, " Applied Solar Energy, vol, 14 , No. 6, 1978, pp 12-17.

29. Sykes, B. R., "Development of Marine Anticorrosive Coatings to the Present Day and Some Thoughts for the Future," American Chemical Society, Division of Organic Coatings and Plastics Chemistry, Preprints, Vol. 39, 1978, pp 473-478.

30. Brumbaugh, George E., "Testing Painted Surfaces," Machine Design, Vol. 46 No.14, June 13, 1974, pp 159-163.

31. Carter, O. L., A. T. Schindler, and E. E. Wormser, "Use of Scanning Electron Microscopy for Evaluation of Paint Film Weatherability ," American Chemical Society, Division of Organic Coatings and Plastics Chemistry, Preprints, Vol. 33, No. 1, 1973, pp 315-324.

32. Matanzo, F., "Senice Life Performance of Marine Coatings and Paint Systems," Journal of Coating Technology, Vol. 52, No. 665, June 1980, p 55.

33. Smith, C. A., "Marine Paint Finishes," Corrosion Prevention and Control, Vol. 27, No. 2, April 1980, pp 13-16.

34. Steptoe, G. G. C., "Marine Atmospheres Provide a Tough Test for Protective Paint Systems," Corrosion Prevention and Control, Vol. 27, No. 2, April 1980, pp 17-20.

35. Fultz, B. S., "Evaluation of Alternative Generic Coatings in Different Ship Areas," IIT Research Institute, Proceedings of the REAPS Technical Symposium, October 14-16, 1980, PP 393-401.

36. Terry, E. S., "A Chemical Coating for Ballast Tanks," Marine En~ineers Review, March 1978.

37. Shimatani, S. and T. Morita, "Performance of Various Coatings on Steel Structures in Marine Atmosphere," Mitsui Technical Review, No. 99, 1977, pp 51-66.

38. "Optimal Paint Systems for Containers," Cargo System International, Vol. 4, No. 12, December 1977, pp 72-75.

39. Roebuck, A. H. and G. C. Cheap, "Recent Advances in Marine Coatings;" Presented at the Corrosion/77" in San Francisco, "

41. Weame, R. B., "Coatings for Ships' Tanks for Sea Water, Potable and Distilled Water, " Fifth Inter-Naval Corrosion Conference, Proceedings, No. 24, 1976.

42. Weaver, W. R., 'Paint 5ystems for the Modern Ship," Fifth Inter-Naval Corrosion Conference, Proceedings, No. 14, 1976.

43. "Inorganic Zinc Coatings for Immersion (Tank Lining) Service," Materials Performance, Vol. I-5, No.6, June 1976, pp 9-14.

44. James, D. M., "Marine Paints," Formulations, (Treatise on Coatings Vol. 4, Pt. 1), 1975, pp 415-482.

45. Rudlowski, G., "Prefailure Evaluation Techniques for Marine " Coatings," General Dynamics Corp., February 1975.

46. Ohnemus, H., "Choose Well Your Coats," Marine Week, Vol. 2, No. 25, June 20, 1975, p 40.

47. Bloodgood, D. T., "Recent Trends in Marine Coatings," American Chemical Society, Division of Organic Coatings and Plastics Chemistry, Preprints, Vol. 29, No. 2, September 1969, pp 1-6.

48. Gelfer, D. H., "Use of Inorganic Zinc Coatings in the Marine Industry," American Chemical Society, Division of Organic Coatings and Plastics Chemistry, Preprints, Vol. Q, No.2, September 1969, p 33.

49. Rogers, J., "Tank Coatings for Chemical Cargoes," Institute of Marine Engineers-Transactions, Vol. 83, No. ~ pp 139-145.

50. Lohr, R. F. and H. Barry, "Prevention of Tanker Corrosion with Modem Coatings. Mobil Chemical Co.," American Chemical Society, Division of Organic Coatings and Plastics Chemistry, Preprints, Vol. 29, No. 2, September 1969, pp 7-20.

51. Klemme, Dorothea E., "Control of Marine Sulfate-Reducing Bacteria in Water-Displaced Shipboard Fuel Storage Tanks," Naval Research Laboratory, No. NRL-MR-2069, Interim Report, December 1969, p 25.

52. Andeqton, W. A., "Phenormma Associated with Metal-Paint Coating Interfaces," Journal of the Oil and Colour Chemists Association, Vol. 53, No. 3, March 1979; pp 181-191.

53. Hearst, Peter J., "Protective Properties of Coatings as Measured by Dew-Cycle Accelerated Weathering," Naval Civil Engineering Laboratory; Port Hueneme, California, January 1970.

54. Isom, Lee E., "Dynamic Evaluation of Experimental Integral Fuel-Tank Sealants. Part I," Systems Research Labs, Inc., Dayton, Ohio; Annual Technical Report; July 3, 1978 to July 3, 1979.

55. "Enviro-ntal Exposure of *Sample* Model Marine Fuel Tanks. UL Assignment 65WW63 File MM-36, UL Assignment 65WW32 File MM-10, " Underwriters' Labs, Inc.; Westwood, New Jersey; Marine Department; Final Report; February 27, 1970.

56. Mallory, William R., Lee E. Isom, and William F. Anspach, ."Bench Scale Dynamic Evaluation Apparatus for Integral Fuel Tank Sealants," Journal of lxircraft, Vol. 17, No. 1.0, October 1980, pp 748-752.

57. van Eijnsbergen, J. F. H., "Optimal Paint Systems for Containers," Cargo Systems International, Vol. 4, No. 12, December 1977, pp 72-73.

58. Nowacki, L. J., B. R. Richards, I. Poretz, and R. J. Welch, "Evaluation of Boottop Paint *Systems* for Ocean Going Ships in Maritime Administration's Boottop Paint Testing Machine," American Chemical Society, Division of Organic Coatings and Plastics Chemistry, Preprints, Vol. 29, No. 2, September 1969, pp 21-32.

- 59. Robinson, A. V., "Tank Coatings," Marichem '80, Conference on Marine Transportation, Handling, and Storage of Bulk Chemicals, London, 1980, pp 169-172.

60. Gelfer, D. H., "Organic and Inorganic Zinc Coatings," 20th Annual Marine Coatings Conference, Louisiana 1980.

- 61. Slade, S., "Alternative Answers in Tank Lining," Chemical Age, Vol. 121, No. 3192, 1980.

62. Van Londen, A. M., "Role of Paint Systems in Optimizing Ship Operations," 4th International Conference on Organic Coatings Science and Technology, Proceedings, Athens, 1978, pp 301-313.

63. Borer, K., "Protection.of Tanks and Pipework," Shipping World and Shipbuilder, 3rd International Ship Painting and Corrosion Conference, Monte Carlo, 1978, Day 1, Paper No. 7, Pp 31-34.

64. Makepeace, R. F., "The Internal Coating of Tanks in Chemical Carriers," Tanker and Bulker International 1976, Vol. 2, March 25, **1976.**

65. Koenecke, D. F., "Reflections on Marine Uses of Zinc-Rich Coatings,"15th Marine Coatings Conference, Alaba+ 1975, Paper No. 3.

66. Kut, S., "Tank Linings," 1st International Ship Painting and Corrosion Conference, Proceedings, London, 1974, pp 131-135.

67. Berger, D. M., "Coatings and Linings for I-rsion Service," Metal Finishin~, Vol. 73, No. 8, 1975, pp 44-47.

68. Stieg, Fred B., "Dew Cycle Weather-Ometer Reevaluated - A Literature Review," Journal of Paint Technology, Vol. 47, No. December 1975, pp 54-62.

69. Stieg, Fred B., "Weathering and Titanium Dioxide," Journal of Paint Technology, Vol. 43, No. 553, February 1971, pp 82-89.

70. Mitton, P. B. and D. P. Richards, "Model for-Objective Development of Accelerated Weathering Tests," Journal of Paint *Technology,* Vol. *43, No. 563,* December 1971, pp 107-114.

71. Hoffmann, E., Weathering of Paint Films and Development of Accelerated Tests," Journal of Paint Technology, Vol. 43, No. 563, Dece~er 1971, pp 97-106.

72. "Inorganic Zinc Coatings for Immersion (Tank Lining) Semite," Materials Performance, Vol. 15, No.6, June 1976, pp 9-14.

73. West, J., "BSRA Survey of Factors Affecting the Performance of Paint Systems," Shipping World and Shipbuilder, Vol. 168, No. 3906, June 1975.

74. Singleton, W. T., Jr., "Performance of Various Coating Systems in a Marine Environment," Materials Protection and Performance, National Association of Corrosion Engineers, Vol. 9, No. H; November 1970; pp 37-43.

75. Banks, M. E., "Study of Protective Coatings in a Tropical Marine Environment ," Journal of Paint Technology, Vol. 42, **No.** 542, March 1970, pp 193-198.

76. "Practical Shipbuilding Standards for Surface Preparation and Coatings," U.S. Department of Commerce, Maritime Administration, Final Report, .July 1979.

77. "Cleaning of Steel Assemblies and Shipboard Touch-Up Using Citric Acid," U. S. Department of Commerce, Maritime Administration, Phase-I Report, May 1980.

78. "Marine Coatings Performance for Different Ship Areas," U. S. Department of Commerce, Maritime Administration, Volume I, July 1979.

79. "Marine Coatings Performance for Different Ship Areas," U. S. Department of Conmerce, Maritime Administration, Volume II, July 1979.

80. "Marine Coatings and Corrosion Control," Maritime Reporter and and Engineering News, Vol. 14, No. 44, July 15, 1982, pp 14-38.

81. Turi, E. A., Thermal Characterization of Polymeric Materials, Academic Press, 1981, Chapter 3, "Thermoplastic Polymers," by S. W. Shalaby, p 290.

APPENDIX A

LETTER FROM SOUTHWEST RESEARCH INSTITUTE TO THE AMERICAN BUREAU OF SHIPPING

S O U T H W E S T   R E S E A R C H   I N S T I T U T E
POST OFFICE DRAwER 2B51O . 6220 CULEBRA ROAD - SAN ANTONIO. TEXAS 7s2s4 - (512) 664-5111

Department of Engineering Mechanics
August 23, 1982

Mr. L. V. Minett
Vice President, Operations Division "
Ameri can Bureau of Shipping
65 Broadway
New York, New York 10006

Reference: SWR1 Project. No. 02-681s

Dear Mr. Minett:

Southwest Research Institute is, conducting a research program (Reference a) for the U. S. Maritime Administration to establish the ability of coatings to permanently seal small weeps* in integral ship tanks. This contract is being administered by Cmdr. L. R. Chirillo through Todd Pacific Shipyards, Inc.

The overall goal of this work is to improve productivity in shipbuilding. If coatings are found to be effective and durable in sealing small weeps, 'then the time required to test tanks can be greatly reduced by using-faster, more efficient leak detection methods and by spending less time in the sealing of weeps. With this approach, testing would still be performed before the application of the coatings.

In a recent research project (Reference b), we established the effectiveness of coatings to seal small holes and weld flaws at pressures of 150 psig. Our results shuwed that typical tank coating systems, when applied at a thickness of 30 roils, sealed holes as large as 161 roils in diameter. Brushed coatings consistently sealed holes 100 roils in diameter and smaller. Sprayed coatings consistently sealed holes of 70 roils diameter and smaller.

Sixty flawed specimens have been coated and tested for leaks as a part of the current project. These specimens each have ten (10) drilled holes ranging in size from 7 roils to 30 roils in diameter. Four different coatings s.vstems have been used to coat the specimens with nominal coating thicknesses ringing from 6 roils to 50 roils. In 40 of the 60 specimens, a stripe-coat was applied-to the holes just before spraying. The other20 specimens were not stripe coated. Leak detection with air and soap at 50 psig gave the following results:

s. "Tank Sealing with Coating Materials," Todd Purchase Order No. PL-44212.

* Weeps, % used here, are characterized by holes which are 10 roils in diameter and smaller.

b. "Improved Tank Testing Methods," U. S. Departmentof Commerce, Maritime Administration, in cooperation with Todd Pacific Shipyards Corp., Jan. 1980,

40 striped specimens: two specimens leaked at the 31-mil-diameter holes

20 unstriped specimens: two specimens leaked at holes of 16 roils in diameter and larger

We believe that the results from Reference 1 and the current project indicate that coatings are effective insealing small weeps. Aging tests are just beginning to determine the- durability of the coatings in accelerated service-like. conditions.

If aging tests on'the coated specimens show that coatincs are still effective for sealing weeps after 10 *or* 20 years of simulated-in-service conditions, then. this property of coatings should be used to advantage in shipbuilding. One way to take advantage of the leak sealing ability of the coatings would be to permit the use of ultrasonic leak detection methods (in place of the soap solution) in the tightness testing of integral ship tanks. At tank pressures of 2 psig, we have shown (see Reference b) that ultrasonic methods can detect 7-roil-diameter holes from a distance of.15 ft and 14-mil-diameter holes from a distance of 25 ft. Thus, ultrasonic methods have obvious potential for making tank testing more productive. Inspection time is also more flexible with an ultrasonic detector than with a soap solution because there is no solution to dry-out and the tank can be inspected as long as it is under pressure. The U. S. Coast Guard has used ultr.zsonic leak detection in ship repair for several years with good results, aiid they have published several instruction booklets on its use.

ABS has already established a precedent in permitting ccatings to seal small weeps in ship tanks by allowing tank testing with weter after special coatings are applied. As discussed above, coatings of 30 roils will seal holes up to 160 roils in diameter at pressures of 150 psig. Six (6)-roil coatings, sprayed or brushed, will seal holes up to 3(I roils at 50 psig. Thus, niany ships are now in service which may have small flaws sealed with coatings.

In summary, we believe that ABS should permit the use of coatings for sealing small weeps in ship tanks if coating durability is found to be adequate in our tests. Further, tank testing requirements should be relzxed insuch cases to"pennit the *use of* ultrasonic detectors in lieu of a soap solution. Me propose that tank testing rules be revised ES follows:

> If the ship tanks are to be 'subsequently coated with a qualified special coating, the ultrasonic leak tie-tection method can be used in lieu of a soap solution in the air test. The leak detection device and the tank coatings must be specially* -approved by the local surveyor.

*We recommend that the ultrasonic leak detector be calibrated to detect a 10-roil-diameter. hole at 10 ft with 2-psig differential pressure across the boundary and that special coatings pass 10- and 20-year accelerated aging tests in the specified cargo(s). These tests, which will measure the ability of the coating to seal holes and weld flaws after aging, will be defined during the current project.

"We request that ABS reply in writing to these recommendations. In addition, we would like to visit ABS to discuss this subject and to present the 1 atest results from our research program. -To give ABS time to study the suggestions presented herein, we propose a visit on September 14. I wi 11 call to confirm this date the week of September 6. Please call me at (512) 6B4-5111 , ext. 2315, if you have any questions or if September 14 is too soon for our visi t.

Sincerely,

W & %

P . A. COX
Senior Research Engineer

PAC/ dl e

CC: W. M. Hannan, ABS
Robert Curry, ABS
E. B. Bowle:, SWRI
R. L. Bass, SWRI

APPENDIX B

TEST DATA ON COATING SPECIMENS

TABLE B.I. TEST RESULTS FOR THE INDIVIDUAL SPECIMENS

Number Plate	Coating System	Stripe Coat	Aging Medium	Weld Holes: Number Before Coating	Weld Holes: Number After Coating	Weld Holes: Number After Aging	Drilled Holes: Number Before Coating	Drilled Holes: Number After Coating	Drilled Holes: Number After Aging	Coating Breakdown Due To Aging	Simulated In-Service Aging Duration	Brand Name	Recommended For This Service
1	Amine Cured Epoxy	Yes		3	1-Vapor		10	0				H1540/3544	--
2				4			10						--
3	Polyamide Epoxy	Yes	Salt Water	3	0	0	10	0	0	None	21 yrs.	A 81/82	Yes
4	Ketimine Epoxy	No	Salt Water	1	0	0	10	0	0	Slight	21 yrs.	I/M TAA	Yes
5	Polyamide Epoxy	Yes	Salt Water	2	0	0	10	0	0	None	21 yrs.	A 81/82	Yes
6	Polyamide Epoxy	Yes	Salt Water	1	0	0	10	0	0	None	21 yrs	A 81/82	Yes
7	Ketimine Epoxy	No	Salt Water	3	0	0	10	0	0	Slight	21 yrs.	I/M EXA	Yes
8	Amine Cured Epoxy	Yes	Methanol	2	0	0	10	0	0	Slight	2 yrs.	H1540/9510	No
9	Ketimine Epoxy	No	JP-4	2	0	0	10	0	0	None	6 mo.	I/M TAA	Yes
10	Ketimine Epoxy	No	JP-4	3	0	0	10	0	0	None	6 mo.	I/M EXA	Yes
11	Polyamide Epoxy	No	Salt Water	13	1-Liquid	1-Vapor	10	0	0	None	21 yrs.	A 81/82	Yes
12	Polyamide Epoxy	Yes	Methanol	4	0	0	10	0	0	None	2 yrs.	A 81/82	No
13	Polyamide Epoxy	Yes	Methanol	2	0	0	10	0	0	Slight	2 yrs	A 81/82	No
14	Polyamide Epoxy	No	Salt Water	3	0	0	10	0	0	None	21 yrs.	A 81/82	Yes
15	Polyamide Epoxy	No	JP-4	2	0	0	10	0	0	None	6 mo.	A 81/82	Yes
16	Polyamide Epoxy	No	JP-4	1	0	0	10	0	0	None	6 mo.	A 81/82	Yes
17	Polyamide Epoxy	Yes	Methanol	1	0	0	10	0	0	None	2 yrs.	A 81/82	No
18	Polyamide Epoxy	Yes	JP-4	1	0	0	10	0	0	None	6 mo.	A 81/82	Yes
19	Polyamide Epoxy	Yes	JP-4	1	1-Liquid	0	10	0	0	None	6 mo.	A 81/82	Yes
20	Polyamide Epoxy	Yes	JP-4	5	0	0	10	0	0	None	6 mo.	A 81/82	Yes
21	Polyamide Epoxy	No		7	0		10	0				A 81/82	--
22	Polyamide Epoxy	Yes		3	0		10	0				A 81/82	--
23	Amine Cured Epoxy	Yes	Salt Water	7	0	0	10	0	0	Moderate	21 yrs.	H1540/9510	Yes
24	Amine Cured Epoxy	Yes	Salt Water	4	0	1-Liquid	10	0	0	Slight	21 yrs.	H1540/9510	Yes
25	Amine Cured Epoxy	No	Salt Water	2	0	0	10	0	0	Slight	21 yrs.	H1540/9510	Yes
26				5			10						--
27	Amine Cured Epoxy	No	Salt Water	11	0	1-Vapor	10	0	0	Some Corrosion Debonding	21 yrs.	H1540/9510	Yes
28	Amine Cured Epoxy	Yes	Salt Water	5	0	0	10	0	0	Slight	21 yrs.	H1540/9510	Yes

TABLE B.I. TEST RESULTS FOR THE INDIVIDUAL SPECIMENS

Number Plate	Coating System	Stripe Coat	Aging Medium	Weld Holes: Number Before Coating	Weld Holes: Number After Coating	Weld Holes: Number After Aging	Drilled Holes: Number Before Coating	Drilled Holes: Number After Coating	Drilled Holes: Number After Aging	Coating Breakdown Due To Aging	Simulated In-Service Aging Duration	Brand Name	Recommended For This Service
29	Amine Cured Epoxy	No	JP-4	5	1-Liquid	1-Liquid	10	0	0	None	6 mo.	H1540/9510	Yes
30				7			10						--
31	Amine Cured Epoxy	Yes	Methanol	6	0	2-Liquid	10	0	0	Severe	2 yrs.	H1540/9510	No
32	Amine Cured Epoxy	Yes	Methanol	7	0	0	10	0	0	Severe	2 yrs.	H1540/9510	No
33	Amine Cured Epoxy	No	JP-4	9	0	0	10	0	0	None	6 mo.	H1540/9510	Yes
34	Amine Cured Epoxy	No		4	1-Liquid		10	0				H1540/9510	--
35	Amine Cured Epoxy	Yes	JP-4	6	0	0	10	0	0	None	6 mo.	H1540/9510	Yes
36	Amine Cured Epoxy	Yes	JP-4	6	0	0	10	0	0	None	6 mo.	H1540/9510	Yes
37	Amine Cured Epoxy	Yes	JP-4	4	1-Vapor	0	10	0	0	None	6 mo.	H1540/9510	Yes
38	Amine Cured Epoxy	Yes		3	0		10	0				H1540/9510	--
39	Ketimine Epoxy	No	Salt Water	6	0	0	10	0	0	Some corrosion debonding	21 yrs.	I TAA Series	Yes
40	Ketimine Epoxy	No	Salt Water	8	0	4-Liquid	10	0	0	Some corrosion debonding	21 yrs.	I TAA Series	Yes
41	Ketimine Epoxy	Yes	Salt Water	6	0	0	10	1-Vapor	1-Liquid 1-Vapor	Some corrosion debonding	21 yrs.	I TAA Series	Yes
42	Ketimine Epoxy	Yes	Salt Water	8	0	0	10	0	0	Some corrosion debonding	21 yrs.	I TAA Series	Yes
43	Ketimine Epoxy	Yes	Salt Water	4	0	1-Vapor	10	0	1-Vapor	Some corrosion debonding	21 yrs.	I TAA Series	Yes
44	Ketimine Epoxy	No	JP-4	5	0	0	10	0	0	Slight	6 mo.	I TAA Series	Yes
45	Ketimine Epoxy	No	JP-4	7	0	0	10	5-Liquid	5-Liquid	Slight	6 mo.	I TAA Series	Yes
46	Ketimine Epoxy	Yes	Methanol	5	0	1-Liquid	10	0	1-Liquid	Severe	2 yrs.	I TAA Series	No
47	Ketimine Epoxy	Yes	Methanol	3	0	0	10	0	1-Vapor 3-Liquid	Severe	2 yrs.	I TAA Series	No
48	Ketimine Epoxy	Yes	Methanol	5	1-Liquid	0	10	0	1-Vapor 1-Liquid	Severe	2 yrs.	I TAA Series	No
49	Ketimine Epoxy	No		9	0		10	2-Vapor 1-Liquid				I TAA Series	--

TABLE B.I. TEST RESULTS FOR THE INDIVIDUAL SPECIMENS

Number Plate	Coating System	Stripe Coat	Aging Medium	Weld Holes: Number Before Coating	Weld Holes: Number After Coating	Weld Holes: Number After Aging	Drilled Holes: Number Before Coating	Drilled Holes: Number After Coating	Drilled Holes: Number After Aging	Coating Breakdown Due To Aging	Simulated In-Service Aging Duration	Brand Name	Recommended For This Service
50	Ketimine Epoxy	Yes	JP-4	8	0	2-Liquid	10	0	0	Slight	6 mo.	I TAA Series	Yes
51	Ketimine Epoxy	Yes	JP-4	8	0	0	10	0	1-Liquid	Slight	6 mo.	I TAA Series	Yes
52	Ketimine Epoxy	Yes	JP-4	5	0	0	10	0	1-Liquid	Slight	6 mo.	I TAA Series	Yes
53	Ketimine Epoxy	Yes		8	0		10	0				I TAA Series	--
54	Phenolic Epoxy	Yes	Salt Water	7	1-Liquid	0	10	0	0	Slight	21 yrs.	PHEN 373	No
55	Phenolic Epoxy	Yes	Salt Water	7	1-Liquid	1-Liquid	10	0	0	None	21 yrs.	PHEN 373	No
56	Phenolic Epoxy	Yes	Salt Water	7	1-Vapor 1-Liquid	0	10	0	0	Slight	21 yrs.	PHEN 373	No
57	Phenolic Epoxy	No	Salt Water	5	0	1-Liquid	10	0	0	None	21 yrs.	PHEN 373	No
58	Phenolic Epoxy	Yes	Methanol	12	0	5-Vapor 3-Liquid	10	0	0	Very Severe	2 yrs.	PHEN 373	No
59	Phenolic Epoxy	Yes	Methanol	10	1-Vapor	2-Vapor 1-Liquid	10	0	0	Very Severe	2 yrs.	PHEN 373	No
60	Phenolic Epoxy	Yes	Methanol	4	0	0	10	0	0	Very Severe	2 yrs.	PHEN 373	No
61	Phenolic Epoxy	Yes	JP-4	7	0	0	10	0	0	None	6 mo.	PHEN 373	Yes
62	Phenolic Epoxy	Yes	JP-4	9	0	0	10	0	0	None	6 mo.	PHEN 373	Yes
63	Phenolic Epoxy	No	Salt Water	3	0	0	10	0	0	None	21 yrs.	PHEN 373	No
64	Phenolic Epoxy	Yes	JP-4	4	0	0	10	0	0	None	6 mo.	PHEN 373	Yes
65	Phenolic Epoxy	No	JP-4	5	1-Liquid	0	10	0	0	None	6 mo.	PHEN 373	Yes
66	Phenolic Epoxy	Yes		10	0		10	0				PHEN 373	--
67	Phenolic Epoxy	No	JP-4	6	0	0	10	0	0	None	6 mo.	PHEN 373	Yes
68	Phenolic Epoxy	No		7	1-Liquid		10	0				PHEN 373	--
69	Coal Tar Epoxy	Yes	Methanol	2	0	0	10	0	0	Slight	2 yrs.	CM 14	No
70	Coal Tar Epoxy	No	Methanol	4	1-Liquid	0	10	0	0	Slight	2 yrs.	CM 14	No
71	Amine Cured Epoxy	Yes	Salt Water	3	0	0	10	0	0	Some corrosion debonding	21 years	C 187 HFP	No
72	Amine Cured Epoxy	No	Salt Water	3	0	0	10	1-Liquid	1-Liquid	Some corrosion debonding	21 years	C 187 HFP	No
73	Coal Tar Epoxy	Yes	Salt Water	7	0	0	10	0	0	None	21 yrs.	CM 14	Yes

TABLE B.I. TEST RESULTS FOR THE INDIVIDUAL SPECIMENS

Number Plate	Coating System	Stripe Coat	Aging Medium	Weld Holes			Drilled Holes			Coating Breakdown Due To Aging	Simulated In-Service Aging Duration	Brand Name	Recommended For This Service
				Number Before Coating	Number After Coating	Number After Aging	Number Before Coating	Number After Coating	Number After Aging				
74	Coal Tar Epoxy	Yes	Salt Water	9	1-Liquid	0	10	0	0	None	21 yrs.	CM 14	Yes
75	Coal Tar Epoxy	Yes	Salt Water	7	2-Vapor	1-Vapor	10	0	0	None	21 yrs.	CM 14	Yes
76	Coal Tar Epoxy	No.	Salt Water	8	2-Vapor	2-Vapor	10	0	0	None	21 yrs	CM 14	Yes
77	Coal Tar Epoxy	Yes	Methanol	8	1-Liquid	1-Vapor 1-Liquid	10	0	0	Slight	2 yrs.	CM 14	No
78	Coal Tar Epoxy	Yes	JP-4	8	1-Liquid	1-Liquid	10	0	0	None	6 mo.	CM 14	No
79	Coal Tar Epoxy	Yes	JP-4	8	2-Liquid	2-Liquid	10	0	0	None	6 mo.	CM 14	No
80	Coal Tar Epoxy	Yes	JP-4	6	0	0	10	0	0	None	6 mo.	CM 14	No
81	Coal Tar Epoxy	No	Salt Water	9	2-Liquid	2-Liquid	10	0	0	None	21 yrs.	CM 14	Yes
82	Coal Tar Epoxy	No	JP-4	4	1-Liquid	1-Liquid	10	0	0	None	6 mo.	CM 14	No
83	Coal Tar Epoxy	Yes		8	0		10	0				CM 14	--
84	Coal Tar Epoxy	No	JP-4	9	3-Liquid	2-Liquid	10	0	0	None	6 mo.	CM 14	No
85	Coal Tar Epoxy	Yes		8	0		10	0				CM 14	--
86	Amine Cured Epoxy	Yes	Salt Water	7	0	0	10	0	0	Some corrosion debonding	21 yrs.	C 187 HFP	No
87	Amine Cured Epoxy	Yes	Salt Water	3	0	0	10	0	0	Some corrosion debonding	21 yrs.	C 187 HFP	No
88	Amine Cured Epoxy	No	Salt Water	2	0	0	10	0	0	Some corrosion debonding	21 yrs.	C 187 HFP	No
89	Amine Cured Epoxy	No	JP-4	5	0	0	10	0	0	None	6 mo.	C 187 HFP	Yes
90	Amine Cured Epoxy	No	JP-4	2	0	0	10	0	0	None	6 mo.	C 187 HFP	Yes
91	Amine Cured Epoxy	Yes	JP-4	1	0	0	10	0	0	None	6 mo.	C 187 HFP	Yes
92	Amine Cured Epoxy	Yes	JP-4	1	0	0	10	0	0	None	6 mo.	C 187 HFP	Yes
93	Amine Cured Epoxy	No		1	0		10	0				C 187 HFP	--
94	Amine Cured Epoxy	Yes	JP-4	5	0	0	10	0	0	None	6 mo.	C 187 HFP	Yes
95	Amine Cured Epoxy	Yes		7	0		10	0				C 187 HFP	--
96	Amine Cured Epoxy	Yes		5	0		10	0				C 187 HFP	--
97	Amine Cured Epoxy	Yes		3	0		10	0				C 187 HFP	--
98	Amine Cured Epoxy	Yes		4	0		10	0				C 187 HFP	--

TABLE B.I. TEST RESULTS FOR THE INDIVIDUAL SPECIMENS

Number Plate	Coating System	Stripe Coat	Aging Medium	Weld Holes: Number Before Coating	Weld Holes: Number After Coating	Weld Holes: Number After Aging	Drilled Holes: Number Before Coating	Drilled Holes: Number After Coating	Drilled Holes: Number After Aging	Coating Breakdown Due To Aging	Simulated In-Service Aging Duration	Brand Name	Recommended For This Service
99	Amine Cured Epoxy	No	Salt Water	4	0	0	10	1-Liquid	1-Liquid	Slight	21 yrs.	A 395	Yes
100	Amine Cured Epoxy	No	Salt Water	5	0	0	10	0	0	Slight	21 yrs.	A 395	Yes
101	Amine Cured Epoxy	Yes	Methanol	3	0	0	10	0	2-Vapor 2-Liquid	Severe	2 yrs.	A 395	No
102	Amine Cured Epoxy	Yes	Methanol	3	0	0	10	0	1-Vapor 2-Liquid	Severe	2 yrs.	A 395	No
103	Amine Cured Epoxy	Yes	Methanol	7	0	1-Liquid	10	0	1-Liquid	Severe	2 yrs.	A 395	No
104	Amine Cured Epoxy	Yes	Salt Water	5	0	0	10	0	0	Slight	21 yrs.	A 395	Yes
105	Amine Cured Epoxy	Yes	Salt Water	4	0	0	10	0	0	Slight	21 yrs.	A 395	Yes
106	Amine Cured Epoxy	Yes	Salt Water	4	0	0	10	1-Vapor	1-Vapor	Slight	21 yrs.	A 395	Yes
107	Amine Cured Epoxy	Yes	JP-4	6	0	0	10	0	0	None	6 mo.	A 395	Yes
108	Amine Cured Epoxy	No	JP-4	7	0	0	10	2-Liquid	2-Liquid	None	6 mo.	A 395	Yes
109	Amine Cured Epoxy	Yes	JP-4	7	0	0	10	0	0	None	6 mo.	A 395	Yes
110	Amine Cured Epoxy	Yes	JP-4	4	0	0	10	0	0	None	6 mo.	A 395	Yes
111	Amine Cured Epoxy	No	JP-4	2	0	0	10	1-Liquid	1-Liquid	None	6 mo.	A 395	Yes
112	Amine Cured Epoxy	Yes		6	0		10				6 mo.	A 395	--
113	Polyamide Epoxy	No	Salt Water	6	0	0	10	0	0	Moderate	21 yrs.	C 191 HB	Yes
114	Amine Cured Epoxy	Yes		4	0		10	0				A 395	--
115	Polyamide Epoxy	Yes	Salt Water	3	0	0	10	0	0	Some corrosion debonding	21 yrs.	C 191 HB	Yes
116	Polyamide Epoxy	No	Salt Water	2	0	0	10	1-Liquid	1-Liquid	Moderate	21 yrs.	C 191 HB	Yes
117	Polyamide Epoxy	No	JP-4	3	0	0	10	1-Liquid	1-Liquid	None	6 mo.	C 191 HB	No
118	Polyamide Epoxy	Yes	Salt Water	3	0	0	10	0	0	Moderate	21 yrs.	C 191 HB	Yes
119	Polyamide Epoxy	No	JP-4	3	0	0	10	2-Liquid	0	None	6 mo.	C 191 HB	No
120	Polyamide Epoxy	No		3	0		10	0				C 191 HB	--
121	Polyamide Epoxy	Yes	Salt Water	5	0	0	10	0	0	Moderate	21 yrs.	C 191 HB	Yes
122	Polyamide Epoxy	Yes	JP-4	2	0	0	10	0	0	None	6 mo.	C 191 HB	No
123	Polyamide Epoxy	Yes	JP-4	5	0	0	10	0	0	None	6 mo.	C 191 HB	No
124	Polyamide Epoxy	Yes	JP-4	2	0	0	10	0	0	None	6 mo.	C 191 HB	No

TABLE B.I. TEST RESULTS FOR THE INDIVIDUAL SPECIMENS

Number Plate	Coating System	Stripe Coat	Aging Medium	Weld Holes			Drilled Holes			Coating Breakdown Due To Aging	Simulated In-Service Aging Duration	Brand Name	Recommended For This Service
				Number Before Coating	Number After Coating	Number After Aging	Number Before Coating	Number After Coating	Number After Aging				
125	Polyamide Epoxy	Yes		3	0		8	0				C 191 HB	--
126	Polyamide Epoxy	Yes		4	0		8	0				C 191 HB	--
127	Polyamide Epoxy	Yes		4	0		8	0				C 191 HB	--
128	Polyamide Epoxy	Yes		3	0		8	0				C 191 HB	--
129	Amine Cured Epoxy	Yes		3	0		8	0				H 1540	--
130	Amine Cured Epoxy	Yes	JP-4	4	0	0	8	0	0	None	6 mo.	H 15-/35-	Yes
131	AMine Cured Epoxy	No		4	0		8	1-Vapor 1-Liquid				H 1540	--
132	Amine Cured Epoxy	Yes	JP-4	6	0	0	8	0	0	None	6 mo.	H 15-/35-	Yes
133	Amine Cured Epoxy	Yes		5	0		8	0				H 1540	--
134	Amine Cured Epoxy	Yes		5	0		8	0				H 1540	--
135	Amine Cured Epoxy	No		5	1-Liquid		8	1-Vapor 1-Liquid				H 1540	--
136	Amine Cured Epoxy	No		3	0		8	2-Vapor 1-Liquid				H 1540	--
137	Amine Cured Epoxy	No		3	0		8	2-Vapor 2-Liquid				H 1540	--
138	Amine Cured Epoxy	Yes		6	0		8	0				H 1540	--
139	Amine Cured Epoxy	Yes		8	0		8	0				H 1540	--
140	Amine Cured Epoxy	Yes	JP-4	4	0	1-Vapor	8	0	0	None	6 mo.	H 15-/35-	Yes
141	Amine Cured Epoxy	Yes		5	0		8	0				H 1540	--
142	Amine Cured Epoxy	Yes	JP-4	6	0	0	8	0	0	None	6 mo.	H 15-/35-	Yes
143	Amine Cured Epoxy	Yes		4	0		8	0				H 1540	--
144	Amine Cured Epoxy	Yes		3	0		8	0				H 1540	--
145	Amine Cured Epoxy	Yes		5	0		8	0				H 1540	--
146	Amine Cured Epoxy	Yes		2	0		8	0				H 15-/35-	--
147	Amine Cured Epoxy	Yes		5	1-Liquid		8	0				H 1540	--
148	Amine Cured Epoxy	Yes		6	0		8	0				H 15-/35-	--
149	Amine Cured Epoxy	Yes	JP-4	10	1-Liquid	0	8	0	0	None	6 mo.	H 15-/35-	Yes

TABLE B.I. TEST RESULTS FOR THE INDIVIDUAL SPECIMENS

Number Plate	Coating System	Stripe Coat	Aging Medium	Weld Holes: Number Before Coating	Weld Holes: Number After Coating	Weld Holes: Number After Aging	Drilled Holes: Number Before Coating	Drilled Holes: Number After Coating	Drilled Holes: Number After Aging	Coating Breakdown Due To Aging	Simulated In-Service Aging Duration	Brand Name	Recommended For This Service
150	Amine Cured Epoxy	No		4	0		8	2-Vapor 3-Liquid				H 1540	--
151	Amine Cured Epoxy	Yes		3	0		8	0				H 15-/35-	--

TABLE B.II. RESULTS OF AGING TESTS IN SALT WATER - ALL COATINGS

Coating Application (No. of Specimens)	Type of Flaw	Number of Leaks Before Coating	Number of Leaks After Coating	Number of Leaks After Aging
Stripe-Coated	Weld Flaws (all)	121	7	4
(24)	Drilled Holes			
	0.007 in.	48	0	0
	0.010 in.	48	0	1
	0.016 in.	48	0	0
	0.020 in.	48	0	0
	0.031 in.	48	0	3
Not Stripe-Coated	Weld Flaws (all)	94	5	11
(18)	Drilled Holes			
	0.007 in.	36	0	0
	0.010 in.	36	0	0
	0.016 in.	36	0	0
	0.020 in.	36	0	0
	0.031 in.	36	3	3

TABLE B.III. RESULTS OF AGING TESTS IN METHANOL/WATER - ALL COATINGS

Coating Application (No. of Specimens)	Type of Flaw	Number of Leaks Before Coating	Number of Leaks After Coating	Number of Leaks After Aging
Stripe-Coated	Weld Flaws (all)	84	3	17
(17)	Drilled Holes			
	0.007 in.	34	0	2
	0.010 in.	34	0	1
	0.016 in.	34	0	3
	0.020 in.	34	0	5
	0.031 in.	34	0	4
Not Stripe-Coated	Weld Flaws (all)	4	1	0
(1)	Drilled Holes			
	0.007 in.	2	0	0
	0.010 in.	2	0	0
	0.016 in.	2	0	0
	0.020 in.	2	0	0
	0.031 in.	2	0	0

TABLE B.IV. RESULTS OF AGING TESTS IN JP-4 - ALL COATINGS

Coating Application (No. of Specimens)	Type of Flaw	Number of Leaks Before Coating	Number of Leaks After Coating	Number of Leaks After Aging
Stripe-Coated	Weld Flaws (all)	149	6	6
(29)	Drilled Holes			
	0.007 in.	48	0	0
	0.010 in.	58	0	0
	0.016 in.	58	0	0
	0.020 in.	59	0	0
	0.031 in.	58	0	2
Not Stripe-Coated	Weld Flaws (all)	80	6	4
(18)	Drilled Holes			
	0.007 in.	36	0	0
	0.010 in.	36	0	0
	0.016 in.	36	1	1
	0.020 in.	36	2	2
	0.031 in.	36	8	6